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Vol. 33. No. 279. March 1947

THE INSTITUTE OF PETROLEUM AND THE INSTITUTION OF FIRE ENGINEERS.

A joint meeting of the Institute of Petroleum and the Institution of Fire Engineers was held at Manson House, 26, Portland Place, London, W.1, on Wednesday, December 11. At the afternoon session the Chair was taken by Mr T. A. Varley (Chairman of the Technical Committee of the Institution of Fire Engineers) and the evening session was presided over by Mr E. Thornton (Member of Council of the Institute of Petroleum).

AFTERNOON SESSION.

Mr T. A. Varley (Chairman), after conveying the regrets of Mr Sullivan, President of the Institution of Fire Engineers, who was unable to attend, said: I would like first to say to the members of the Institute of Petroleum how delighted we are, as members of the Institution of Fire Engineers, to have the opportunity to join with you in this meeting, to hear and to discuss a most interesting and valuable series of lectures. We in the Fire Service, of course, have very vivid memories of the responsibilities that have rested on your shoulders in connexion with the care of petroleum, the country's lifeblood during the war. We recall many incidents in which we have played a part, and we do welcome this opportunity of discussing mutual problems.

Mr E. P. Lancashire presented the following paper, which he illustrated by means of numerous lantern slides of the incidents dealt with in the paper, as well as by a film; a further film illustrated some early experiments on base foam injection.

FIRES AND EXPLOSIONS AT OIL INSTALLATIONS.

By E. P. Lancashire (Member).

During wartime service with the Petroleum Board, it was one of the author's allotted tasks to prepare reports on any major petroleum fire or incident that occurred and which affected any of the Petroleum Board's activities, the purpose being to study the cause of the incident, the physical means adopted, and the subsequent result.

Although in several cases the fire had been extinguished before my arrival at the scene of the incident, it was nevertheless possible to study first hand most of the happenings of any importance that have occurred during the past few years, and the major facts are now submitted for open discussion.

Mr. V. J. Wilmoth, in his paper "Some Notable Wartime Oil Fires" (*J. Inst. Petrol.*, 1946, **32**, 1), dealt comprehensively with incidents in which the N.F.S. were concerned.

This paper must of necessity to a certain extent be historical and deal

again with some of those incidents described by Mr. Wilmoth, but for the purpose of discussion it is felt desirable to give all the technical details.

As Professor F. H. Garner said in the discussion following Mr. Wilmoth's paper, it is a tribute to the fire-preventative steps taken by the petroleum industry that so few fires occur during peacetime.

In wartime, however, the industry is faced with unknown quantities, each event bringing with it fresh difficulties, and tribute should be paid to all those in the industry, both management and personnel, and the Fire Service, who have over the past years given of their best under hazardous conditions, and whose efforts, some of which have received official recognition, were the means of minimizing the destruction of both plant and product.

The experiences gained brought about the adoption of new methods, and whilst it is agreed that the conditions of war are not present in peacetime, it is suggested that the knowledge gained and the lessons learnt can be applied with advantage in normal times.

Salt End—July 1940.

This fire presents some rather interesting points. During the late afternoon a few bombs were released about this installation, one falling and exploding in a bunded area approximately 40 ft from an above-ground 3000-ton capacity storage tank, containing a stock of 2620 tons petroleum spirit. The splinters from this exploding bomb punctured the tank side-plates to a height of about 10 ft over an arc of about 45 ft, the punctures varying in size from $\frac{1}{2}$ inch diameter to elongated holes $2\frac{1}{2}$ inches long by $\frac{3}{4}$ inch wide. Spirit released at these punctures was fired, presumably by the hot fragments, and this spouting burning spirit soon created an area of burning product within the tank bunded area.

Jets of water were used in an effort to extinguish the burning product which was being ejected from the tank side, and foam was used to control the area. Little success was met with, however, and other operations were put into effect.

The tank involved happened to be equipped with two internal swing arms. Men protected by means of a water screen went to the tank side and adjusted the level of each swing arm, so that one was lowered within a short distance of the tank floor and the other lifted above the level of the highest puncture. The tank side-valves were opened and water pumped into the tank via the lower swing arm by transfer from another tank, product being withdrawn via the higher swing arm and placed into other storage some distance away. At the outbreak of war, by prior arrangement, certain storages at installations had been sterilized, some being filled with water, in order to isolate tankage and reduce the risk of extensive damage. Such happened to be the case here, and the water-filled sterilized storage provided a useful source of supply for transfer to the damaged product tank.

After about 4 hours dual pumping, sufficient water had been transferred to lift the product above the level of the highest puncture, when only water exuded from the holes and enabled burning product in the tank area to be extinguished with foam. Whilst the withdrawal of product

was undertaken in order to prevent an overflow during the period of injecting water, it was also necessary for the speed of pumping to be synchronized as far as possible so that the rate of offtake of product did not to any appreciable extent exceed the rate of water input, thus maintaining a fairly constant ullage and preventing a dilution of gases in that space to within the explosive range.

During this period, however, the tank roof-plates had parted from the periphery curb over a length of approximately 50 ft, due to heat from the area fire fusing the aluminium rivets of the periphery joint. This allowed gases exuding at this point to be ignited, and although a good blanket of foam was placed on the surface of the remaining product in the tank, by means of portable appliances passed through the roof manholes, it did not appear to have any effect. Both swing arms were, therefore, placed on withdrawing the remaining product and a temporary 4-inch steam line and hose was laid below the roof. By this means all flame was finally extinguished, although only after a further 16 hours, with a total product loss of 390 tons. I would say here that the roof fire proved the more difficult to deal with. The tank roof was not disrupted and, as has been shown in subsequent cases, the foam blanketing of the product in such instances has no apparent effect on the confined rich gases on fire which are not subject to dilution by free mixture with the atmosphere that would accelerate its consumption by burning, but it is not usual to equip storage tanks with two swing arms, and the method employed here cannot, therefore, be generally adopted.

It was also evident from this incident that had the tank been protected in some physical way, it would not have been punctured, and, as was shown in the following years, the provision of curtain walls around above-ground storages was amply justified and was the means of preventing damage of this nature to tanks in service.

Purfleet—September 1940.

At the start of intensive activity over the Thames area at this time, this installation was the subject of a particularly heavy attack when twenty-six above-ground main storage tanks, representing a total tonnage of 55,000 tons, were set on fire—four tanks contained spirit, six tanks kerosine, ten tanks fuel oil and six tanks lubricating oils. In addition to these there were eleven smaller tanks attached to the refinery section also involved, a number of rail trucks containing barrels, rail cars and several installation buildings and their contents.

The erection of curtain walls had commenced, but only one tank had been completed and one partially complete whilst the remainder were devoid of protection, resulting in several being badly punctured and creating a terrific ground fire.

The total area involved was about 11½ acres, and it will be readily realized that all services such as pipelines, both product and water, and approaches to the various bunded areas were disrupted, and as a consequence all normal practices which might be used in dealing with petroleum tankage fire were brought to nought. All efforts were exerted to prevent the fire from spreading to other storage, and ultimately to drive it back to

some centre point, and success was met with after three days, which time it will be agreed speaks well for the work of the people engaged.

During the period the area referred to was on fire, an underground tank on an adjoining site received some damage. This tank formed one of a group of tanks, each having a capacity of about 3400 tons, and contained 3000 tons of petroleum spirit. It was of steel multi-arched design, 15 ft 6 in deep, the steel roof being covered with 6-inch reinforced concrete and earth. The bomb falling on it had presumably exploded on impact, forming a crater about 40 ft diameter and disrupting the roof for about 20 ft square, slightly off centre, the debris of steel, concrete and earth falling into the tank. No fire resulted and little stock was lost.

Again within the few weeks that followed, two further underground tanks on the same site and of similar size and design were subjected to equal damage, and again no fire resulted.

In January 1941, however, a fourth underground tank of similar size and design on this site was damaged. On this occasion a crater was formed at one corner of the tank, disrupting a portion of the roof and creating a breach in the tank side at this point approximately 12 ft × 6 ft. The tank contained only about 200 tons of petroleum spirit which would mean that there existed about 14 ft depth of gas space. Fire immediately resulted without any smoke formation and was obviously a gas fire in its true sense, as apart from a normal product fire. Foam appliances were used, but their application was difficult, and considerable quantities of foam were undoubtedly destroyed by passage through the heat. This is understandable when it is realized that the product level would be about 17 ft below ground level. In all, approximately 2000 gal of foam-making compound were used and it took 4 hours to extinguish the fire.

PURFLEET—SEPTEMBER AND OCTOBER 1940.

About the middle of September, a 5500-ton tank located in another installation in this area, and containing approximately 3500 tons of marine fuel oil, received damage. In this case it is presumed that the bomb penetrated the tank roof and detonated within the body of the oil. The explosion split the tank side from top to bottom, splaying the plates outwards and allowing the roof to collapse. The entire content was thereby released over the works and adjoining buildings, flooding parts to a depth of about 3 ft. The tank had not been protected with a curtain wall and no fire resulted. Salvaging of the oil was commenced by means of emergency steam pumps placed in convenient positions, and after a few weeks of these operations, the product, although in a wet condition, had been recovered into other storage with only about a 15 per cent loss.

Some few days, however, after salvage operations had been completed, the installation was the object of a second attack, when a bomb exploded in a tank area bund wall. The explosion demolished the bund wall for a distance of 30 ft, formed a large crater and splinters punctured six storage tanks having a total capacity of 9500 tons, containing fuel oil. These tanks did not have curtain wall protection and one was very badly punctured in numerous places from top to bottom, the holes ranging in size from ½ in diameter to 4 in × 2 in. Five of the punctured tanks did not

immediately fire, but the sixth contained a stock of waste oil having a high water content, and standing at a temperature in the region of 100° F. The released oil from this tank fired immediately, and before preventative steps could be taken involved the remaining punctured tanks and others within this area. Unfortunately, the ground about these tanks was in an oil-saturated condition following the release of oil from the tank previously described, and this undoubtedly aided the rapid spread of fire on this occasion, involving a large track of product pipelines placed on ground level and causing their destruction.

Transfer of product to safer storage was undertaken from some tanks, thus saving a considerable tonnage, and foam branch pipes were brought into action on the fire, but certain fire fighting personnel persisted in using water jets which tended to aggravate the condition. Ultimately, however, the fire was extinguished after a burning period of only 10¼ hours during which period 1006 gal of foam-making compound had been consumed.

This was a further incident which might not have happened had the tanks been protected with curtain walls, and it also forcibly indicated the necessity of the outside fire-fighting personnel being guided in their activities by the people in charge of an installation who have expert knowledge not only of the plant, but also of the product involved and its reaction to fire. Water in its naked form, had, it is felt, been used excessively, and at one stage brought about a slop-over in a tank which destroyed the foam blanket on the ground area and re-ignited the flooded oil. A further point of interest was the strenuous efforts of the installation staff in plugging the tank-side punctures with wooden pegs. The exuding oil was at a high temperature and the men were in danger of being scalded, but this action most certainly was the means of saving a large tonnage from destruction.

Avonmouth—January 1941.

A small tank of 1100-tons capacity and full of kerosine received a direct hit. The tank had been brick protected and the walling was badly cracked. The tank roof was completely wrecked, some plates being thrown a distance away and the contents were fired. As the tank was full of stock, a quantity was pumped away to other storage in order to create sufficient ullage in which to build a foam blanket, when appliances were brought into operation and the burning product extinguished in 45 minutes. An adjoining tank containing petroleum spirit had a large section of its brick curtain wall demolished, and although the true reason for this is not known it is certain that the curtain wall saved this tank from further damage.

Avonmouth—March 1941.

This incident was quoted by Mr. Wilmoth in his paper, but should again be referred to as it brings to light some interesting points not previously indicated. As has been stated, the tank received a direct hit, the explosion causing the entire area of roof plates to be blown off, the roof landing intact but in a badly crumpled condition over the bund wall of the tank compound, and coming to rest across some railway tracks.

The photograph which accompanied Mr. Wilmoth's paper was incorrectly styled as representing a view of a tank which has completely collapsed.

The tank had a capacity of 6800 tons and contained 4850 tons of petroleum spirit. The brick curtain wall was partially demolished, the top plates of the tank buckled inwards for a distance of about 4 ft down, and the main outlet valve was badly distorted, causing it to leak. The contents of the tank immediately fired, but as the level of the product was below the level of the upper disrupted plates, no spillage from that cause took place, although fire quickly spread to the compound, igniting the product released from the tank side-valve. The displaced roof on falling had fractured some product pipelines, causing an intense fire in the pipe trench below the fallen roof. Linked with this incident a spirit can- and barrel-filling building and its contents were fired by incendiary bombs. Bombs had also fallen amongst other storages, but the brick curtain walls, although cracked and scarred, had prevented damage to the tanks themselves.

Due to its location and the direction and force of the wind, there was some difficulty in approaching the tank on fire, and after 1½ hours burning an adjoining tank containing 3800 tons of vaporizing oil became involved. This tank had been completely brick protected, but the roof plates had been badly disrupted by the explosion in the spirit tank which prevented efficient cooling on that area. Some 2½ hours later, two further tanks became involved, one of 2000 tons capacity, brick protected and full of kerosine, the other a small tank containing a small quantity of aviation fuel and unprotected.

At the end of 15 hours the large spirit tank had burned itself out with total loss of its contents, the curtain wall completely collapsing and the shell plates collapsing over two-thirds the tank circumference. At this stage both the vaporizing oil and kerosine tank continued to burn, a third of the curtain wall around one having collapsed, the walling of the other being badly cracked with large sections lying outwards at an angle of about 5° from the tank side, and both tank roofs had collapsed.

As it was considered that the best use was not being made of appliances, the installation officials recommended a complete re-organization of the fire-fighting activities. Some foam branch-pipes were being used to project water streams on to the tank sides for cooling whilst foam was also being used for this purpose. In addition, due to the great number of hoses laid out, some had been incorrectly coupled, nullifying the use of certain equipment. The re-organization took the form of a concerted attack on both the remaining tanks at the same time with a number of foam-making branch-pipes, one tank being tackled from the west, the other from the east, but in each case efforts were made to merge the foam jets together so that a solid flow of foam impinged on the inner wall of each tank on the windward side. These operations proved successful when the kerosine tank was extinguished in ¾ hour after having been on fire 13 hours with a loss of 45 per cent of its contents. The vaporizing oil tank was extinguished in 1½ hours after having been on fire 17 hours with a loss of 70 per cent of its contents. Unfortunately, fire again developed in the vaporizing oil tank about 2 hours later, due, it is believed, to the presence of hot carbon deposit on the underside of the inwardly

curled tank shell plates. This renewed outbreak, however, was extinguished in one hour.

Thames Haven—April 1941.

The points of interest in this occurrence are mainly the effect of terrific blast on storage tanks and the method employed to deal with a particular burning product. Most of the explosive charges dropped on this occasion consisted of parachute land-mines. One of these missiles exploded among a group of large tanks, completely destroying two of 70 ft diameter, empty and unprotected. A third of 80 ft diameter, unprotected, contained a stock of creosote. This tank was badly punctured, allowing the creosote to flood the compound, where it fired, involving an area of approximately $1\frac{3}{4}$ acres. This creosote fire was extinguished in 3 hours by the sole use of water jets; the water, due to the difference in gravity, flowing over the creosote without emulsifying it, and smothering the flames.

When the explosion occurred a shell plate from one of the tanks destroyed was thrown a distance of about 200 yd, hitting an unprotected tank containing petroleum spirit, the plate adhering to the tank side in the form of a plaster about 10 ft from ground level. A further large section of plate was thrown in another direction, hitting an 80-ft diameter tank, empty and unprotected, about 130 ft distant, piercing the tank side, causing an irregular hole about 8 ft × 5 ft, passed through the tank, making a similar irregular hole in the opposite side and finally coming to rest about 100 ft beyond.

A second land-mine which exploded in another part of the installation about half an hour later, formed a crater about 20 ft deep and 50 ft diameter between a group of three 80-ft diameter tanks. Two of these tanks were empty of stock and unprotected. The tank sides were blown in and one was moved off its bed about 4 ft. A further tank some 50 ft away had its roof badly damaged and its small stock of heavy oil fired. The depth of stock in the tank was only 2 ft, and although foam appliances were used, it took about 5 hours to extinguish the fire.

Eccles—May 1941.

During activity in the North-West Area a 5250-ton capacity storage tank, containing 450 tons fuel oil, received a direct hit. The bomb penetrated the roof and there was evidence that the explosion took place inside the tank. The roof was blown off in three separate sections, one section being carried a distance of 85 ft over an adjoining tank and coming to rest against the curtain wall of a storage tank without causing damage. A second section was also thrown against the walling of another tank, whilst the third was thrown a distance of 165 ft on to the pumphouse roof. When the explosion occurred, the product stock was fired, splinters from the bomb piercing the side plates from the inside. The tank had been brick protected for its full height, and although the tank side-plates were punctured, the splinters did not penetrate the outer brickwork and this undoubtedly saved adjoining storage tanks in close proximity from damage.

At the outset there was some delay in dealing with the burning tank, due to the disruption of pumping gear and the lack of pressure in the water mains, and it was necessary to institute emergency water pumping from a nearby canal. With this means appliances operating on chemical foam powder were brought into use, but control of the fire could not be gained. The tank had an ullage of 33 ft through which depth of heat the foam had to fall before reaching the product level and the tank eventually burned itself out after a period of 5 hours and was completely destroyed.

In all, 2400 lb. of foam powder were consumed, representing a foam depth of 6 in for this size of tank. It was seen, however, that little foam had found its way into the tank, whereas the roofs of a row of cottages some yards distant had been covered with a perfect foam blanket. This forcibly indicated the necessity for the scientific operation of foam equipment, which will be dealt with later.

Barton—May 1941.

At the time the aforementioned incident occurred, this installation also received damage involving two separate areas.

A parachute land-mine exploded between a group of three 64-ft diameter storage tanks containing a total of approximately 3100 tons lubricating oil. The work of erecting brick protection walls around these tanks had only just commenced, and for the most part had only reached a height of 5 ft. Protection, therefore, virtually did not exist, with the result that the tanks were very badly disrupted, the oil stock being thrown into the air and ignited, the fire spreading over the whole compound. The explosion had also demolished abour 100 ft of bund wall which allowed the released oil on fire to spread over railway sidings and involve rail cars and stocks of barrelled fats. The heat from the burning lubricating oil became very intense and the remaining tank structure rapidly collapsed, necessitating the area from a fire angle to be treated as a whole, but after 15 hours, although it was under control and practically extinguished, one tank gave some difficulty. This tank had completely collapsed inwards, leaving some oil burning in the area below, which could not be approached. A hole was therefore cut by burning in the collapsed tank side-plates, through which a foam branch was inserted. Whilst the man was cutting the hole, protection measures were laid on in the event of fire exhausting through the opening made.

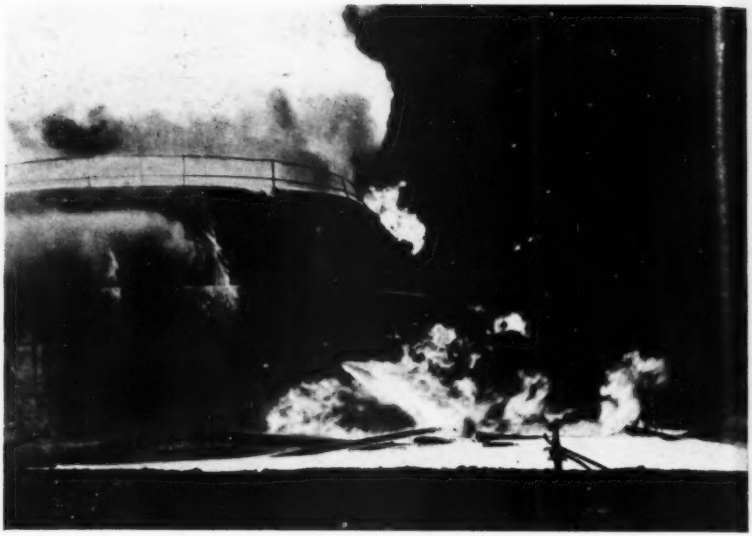
About half an hour after the start of fire to the three tanks referred to, two bombs fell in the main section of the installation, one making a direct hit on a 75-ft diameter tank, containing 1400 tons of lubricating oil, the other making a direct hit on a 57-ft diameter tank containing 400 tons of lubricating oil.

The first tank had not been brick protected and there was evidence of the bomb piercing the roof, the explosion ripping the side-plates practically from top to bottom, releasing the entire oil contents, which fired immediately, into the surrounding compound. The second tank, which had been bricked for about a quarter of its height, was not disrupted and, although the roof was damaged and the oil content fired, no product was released into the compound.

PURFLEET.

Punctured fuel-oil storage tank plugged with wood pegs.

[*To face p.* 138.

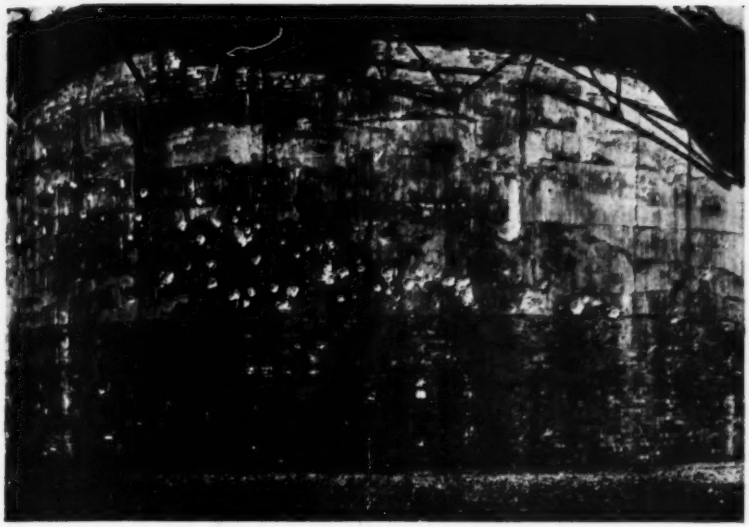


PURFLEET.

Note burning product exhausting through punctured tank sides into compound.

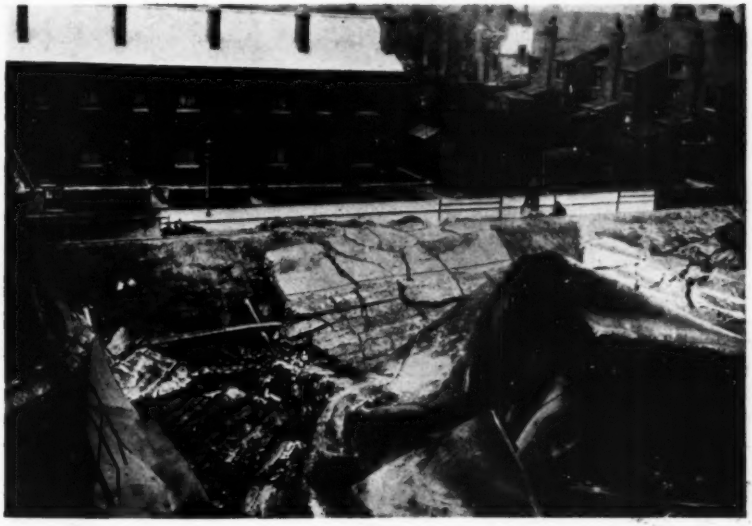
PURFLEET.

Main pipe-track destroyed by ground oil-fire.



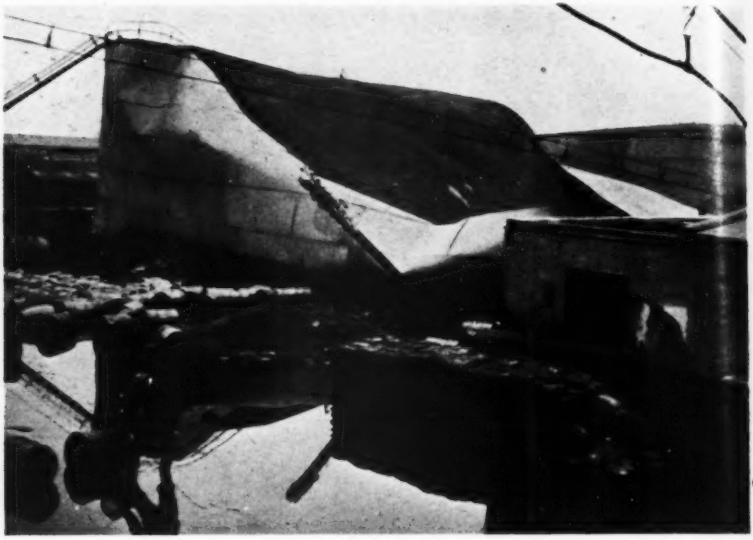
AVONMOUTH.

Showing how curtain wall saved storage tank from puncturing.



ECCLES.

Burned-out tank in foreground. Note collapsed curtain wall, also foam blanket carried away by up-draught from tank and deposited on houses and road.

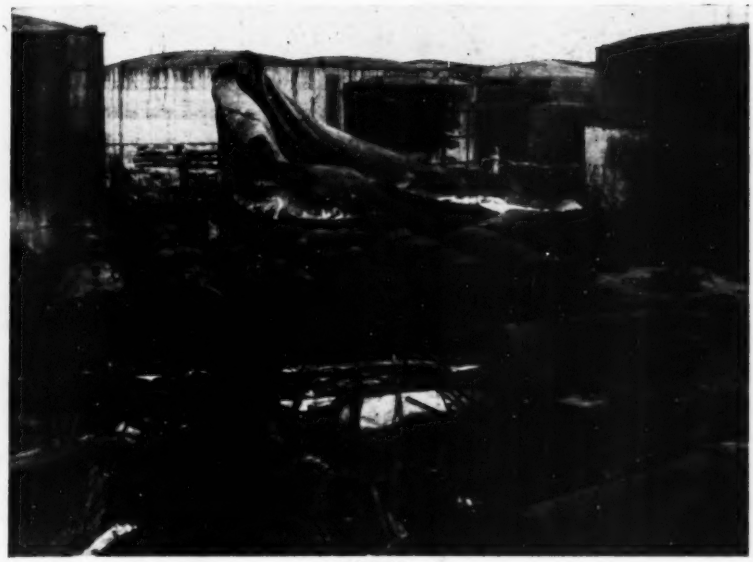


PURFLEET.

Collapsed tank following internal explosion. Note released fuel oil flooding area.

THAMES HAVEN.

Showing effect of blast.



BARTON.

Collapsed steel structures, due to heat from ground oil fire. Cylinders in foreground were elevated before fire.

BARTON.

Collapsed overhead pipe track, due to heat from ground fire.

BARTON.
Vitrified brickwork of curtain wall.

POOLE.
Destroyed underground storage tank. Spirit content did not fire.

The level of the released oil in the compound rose very rapidly, spreading beneath 18 elevated 12,000-gallon cylinders, causing their collapse due to the weakening of the steel supporting structure under heat. From here it flowed to oil blending and filling sheds, causing them to fire and collapse. All this debris and collapsed structures, it can be well imagined, prevented the operation of appliances on the seat of the fire, and whilst the areas accessible containing the greater depth of oil were treated with foam, the extremities were controlled with water jets to prevent other storage tanks becoming involved.

Due to a slight difference in ground level, however, the released oil in one area rose to a depth of about 2 ft 6 in, and coming into contact with steel flood gates, caused them to distort, permitting the burning oil to spread further over the installation and involve the boiler house. An emergency sandbag wall was built and this again controlled the flooded area.

It took approximately 15 hours to extinguish this fire, the entire stock of oil in the two affected tanks being destroyed, and a great deal of damage was done to buildings and plant. Other main tanks and their contents were, however, saved from any great damage.

The points of interest here were mainly the effects of heat on certain structures. Heat produced and radiated by a large quantity and area of burning lubricating oil is by far greater than that produced by a petroleum spirit fire; and not only does this make fire fighting more difficult, but it also brings about the more rapid collapse of structures, although in one area where burning oil came into contact with brickwork, the brickwork was vitrified but did not disintegrate.

In previous incidents the effect on pipelines of burning products released into areas had quickly brought about their destruction, thereby isolating tankage. At this stage an active programme of earth covering exposed pipelines within storage compounds had already been put in hand, the main purpose being to give the pipelines protection against flying splinters.

Such was the case here, but it was interesting to see that all pipelines within the large area covered with burning oil and which had only been covered with about 6 in of earth, were intact, although completely exposed sections had been destroyed.

Again, as has been mentioned, free oil burning over an area soon weakens the steelwork supporting service tanks and other plant, should the oil flow around such structures. Invariably the point of weakening is approximately 12 in above the level of oil on fire, and to minimize the possibility of damage from this cause, it was decided to protect the base of all steel columns in such areas with brickwork to a minimum height of 5 ft.

In order to prevent any possible future distortion of steel flood gates, others were protected with a facing of foam slag.

OULTON BROAD—MAY 1941.

This incident, although not actually involving fire, has its interest.

A bomb penetrated the roof of a 50-ft diameter × 30-ft high storage tank, containing approximately 13 ft depth of kerosine. The bomb formed a 12-in diameter hole in the roof plates, passed through the pro-

duct, penetrated the tank floor and detonated in the tank bed. The explosion tore the floor plates, curling them inwards and formed a hole about 6 ft in diameter. The tank shell plates were also sheared for about a quarter of the tank circumference and over a height of 15 ft from the tank bottom. This tank had been protected, but the brick walling over this area was demolished and the kerosine content released over the compound, although, as has been said, it did not fire.

Emergency salvage pumping was put in hand and practically half of the tank stock was recovered.

POOLE—JUNE 1942.

Here also the incident did not involve fire, but again, in view of previous debate it has its degree of interest and involves a completely buried storage tank, full of petroleum spirit.

The tank was one of 118-ft diameter × 19 ft 8 in deep, steel lined, the sides having an outer skin of reinforced concrete. The tank roof was formed of reinforced concrete supported on steel columns, the whole being covered with earth.

A bomb, believed to be of 500-kilo calibre, hit the tank roof at the side of the tank nearest to the pipeline tunnel. It penetrated the concrete roof, fell through the spirit content and from subsequent examination, appeared to have exploded on the tank floor or penetrated the floor and then exploded. The explosion blew off half of the concrete roof area, threw several tons of spirit into the air, blew out the tank sides adjacent to the tank tunnel, causing a large crater at this tunnel and a gap in the tank side from top to bottom of about 4 ft, tearing the reinforced concrete wall. Several internal columns collapsed, followed by debris, and a section of the tank floor plates were curled inwards.

Although this tank was so badly disrupted and some of its contents of petroleum spirit thrown out, the remainder escaping through the fractured side, the product did not fire.

The main concern, therefore, was salvage. Emergency pumps were brought into action; these including fire trailer pumps, but preventative steps against possible fire were taken by covering some of the exposed areas with foam. This was considered advisable in view of the presence of an unexploded bomb of believed heavy calibre some few hundred yards distant.

Salvage operations by these means were continued for four days and nights, when 850 tons were recovered into other storage.

At one stage a bomb crater some distance from the damaged tank and into which spirit was flowing from the surrounding ground, was converted into a convenient reservoir by the erection of sandbag walls around it. This provided an efficient suction point for emergency pumps.

Further a large tonnage had flowed on to an inland lake, and at one time lay ½ in deep on the water surface. By cutting trenches through an adjoining marsh, a considerable quantity of this product, helped by the wind, was encouraged to flow to another convenient suction position where several thousand gallons were recovered by means of a special oil recovery tank designed for recovering oil from water.

FALMOUTH—MAY 1944.

This incident also was described by Mr. Wilmoth, but should be referred to again as some interesting points from a fire-fighting angle, not previously discussed, were experienced.

As has been mentioned, a bomb fell on to a 4000-tons capacity tank full of petroleum spirit. The tank was a buried one 118 ft diameter × 19 ft 8 in deep, steel lined and having an outer skin of reinforced concrete. The roof was of reinforced concrete, supported on steel columns and covered with 2 ft 6 in of earth.

It is believed that the bomb detonated on impact, disrupting the whole of the roof area, causing it to collapse into the tank and throwing out a considerable tonnage of the spirit content. The product immediately fired, spreading over a similar tank in an adjoining compound adjacent to which was a bomb crater that had been filled with product thrown from the disrupted tank. The explosion also split the tank side at the pipeline tunnel and fractured the pipelines, thus allowing a free flow of product on fire to a vehicle loading yard some 30 ft below and thence to a stream running in some low ground in front of the installation. The explosion also blew in the tank tunnel walls so that they met at the tank side, but the tunnel roof remained intact.

Product from the tank in the adjoining compound, which at one stage was under fire, was transferred without loss to other storage and it was subsequently found that the explosion of a nearby bomb had blown in the steel lining over about an eighth of the circumference, although there had been no shearing of the plates or welded seams.

The flow of spirit on fire was about 600 yd and in parts 100 yd wide, destroying in its path installation buildings, affecting nearby private dwellings by radiated heat, and spreading over three roads which made approach to the source of the fire difficult for fire appliances and personnel.

At the time the explosion occurred the installation fire water main was fractured, but emergency supplies from a nearby lake were obtained through a surface main already laid and nine No. 10 foam branch pipes were operated on the exposed surface of the disrupted tank. This application extinguished the burning product remaining in the tank in 8 hours, but spirit continued to flow on fire over the lower ground and this area proved more difficult to deal with.

The plan employed was to divide the fire into three areas, in an effort to make use of the roads, which were at a slightly higher level, as barriers. In addition, artificial dams were formed, using empty steel barrels and planks against which a blanket of foam could be built. Burning product was flowing at a fairly high rate over the falling ground which resulted in foam being carried with it. It is far easier, as will be imagined, to apply an efficient foam blanket over a static surface than it is a moving surface which has no particular defined boundary. Again, there were periods when foam was only intermittently applied and during which time water spray was used. This method was most unsuccessful, resulting in re-ignition of areas. At one point a flash back occurred over a roadway, destroying a major fire unit. A further difficulty encountered was caused

by the frequent ignition of gas pockets which destroyed the foam blanketting, bringing about re-ignition.

The ground formation about this area was a type of shale, the surface of which became very hot. Product from the disrupted tank had leaked into the ground, flowing through the shale strata, where it was presumably vapourized and exhausted under pressure at unexpected points. The phenomenon took the form of a sudden explosion followed by a vortex of burning gases and smoke rising many feet.

A concerted effort with foam appliances, however, finally extinguished the whole area after a burning period of 21 hours.

Free spirit continued to flow beneath the foam blanket, but this was trapped at an artificial dam built into the stream in the form of an interceptor and pumped away through temporary lines into storage. Salvage operations had proceeded for 20 hours, when, for some unknown reason, the centre area re-ignited. This second fire was extinguished in 2 hours, but the additional flow of water washed away the salvage interceptor, resulting in further loss of product and only about 100 tons was actually recovered.

LLANDARCY—SEPTEMBER 1945.

This incident was not the result of enemy action, but, nevertheless, its cause and effect are of equal interest and it was reported on at the invitation of the National Oil Refineries, Ltd.

An above-ground tank 116 ft diameter × 40 ft high, having a fixed roof with single row rivetted periphery seam, and protected with a 10-inch thick mass concrete and 4½-inch brick wall constructed close to the tank side for its full height, had been placed out of service for structural repairs. The tank had contained petroleum spirit and although the major bulk of the stock had been removed, it is believed that there may have been pools of spirit lying on the floor, as the tank had not been operated with a water bottom. A fitter and his mate were detailed to open up the tank for gas-freeing. They first opened the roof manhole lids and then removed the bottom manhole covers.

It has been the practice when constructing protection walls around storage tanks to also protect the bottom manholes, and in many cases this was done by forming a chamber around each bottom manhole, bounded by brick walls and having a concrete roof. Such was the case here, and when the fitter had completed his task, his mate decided to return to one chamber for the purpose of repositioning the removed manhole steel cover, as he considered it had been left in a way that prevented free entry into the tank.

Obviously, in view of the tank's condition with both top and bottom manholes open, there would be a heavy concentration of petroleum vapour in the confined area the man entered. On lifting the heavy steel cover, weighing about 185 lb, he was partially overcome, the cover falling against the concrete or brickwork, whereupon the man was enveloped in fire. It is believed, in the absence of any other reason, that the falling steel cover produced a spark of sufficient density to ignite the vapours in the area.

The vapours at this point would be too rich to explode, but it is believable that they may have been within the inflammable range.

On the arrival of works fire parties, ignition of vapour had taken place through the tank, and gases were burning at both bottom manholes.

Water in atomized form was applied by means of spray nozzles to both bottom manholes and surrounding brickwork, in an effort to extinguish the flames and also to cool the surrounding brickwork, so preventing its collapse. On a few occasions, the water spray temporarily extinguished the fire at one manhole, but this was accompanied by a noticeable increase of fire at the opposite opening and almost at once re-ignition took place. During one of these periods it was seen that vapours were burning inside the tank adjacent to the manhole and a few feet from the tank side, whilst further into the tank could be seen a swirling vortex of semi-luminous flame extending upwards towards the underside of the roof.

At this stage the tank protection walling commenced to develop cracks in a vertical position about the tank top and through these it could be seen that the tank side plates were getting extremely hot. The tank had been equipped with four size No. 30 fixed foam branch pipes, each having a goose-neck connection to the tank side just below the roof angle curb and, after about 50 minutes burning, it was decided to operate these fittings in order to cool the tank side-plates, thereby preventing them from becoming weaker than the tank roof, and minimizing the risk of possible damage to other storage in the vicinity, should an explosion occur.

It was felt, however, that whatever means were adopted, an explosion was inevitable, as the burning gases inside the tank were rapidly being diluted by the induction of air through the open top manholes.

Good quality foam was seen to be falling down the tank sides past the bottom manholes but, after 15 minutes application, an explosion occurred which lifted the tank roof about 10 ft, this then falling inside the tank. The collapse of the roof caused an increase of flame at the bottom manholes, and was followed by an intense fire within the tank accompanied by volumes of smoke, but within 10 minutes the tank had burned itself out. The explosion fractured all the fixed foam branch pipe goose-necks, leaving the open-ended pipes, from two of which foam continued to be ejected vertically until shut off. It also increased the cracks in the outer brick walling and within a short time two areas from top to bottom, and each about a quarter of the tank circumference, fell away towards the tank area bund wall.

Observations.

Protection Measures.

The erection of walls either close to the tank side, or a few feet away where the ground was unstable, was certainly of untold value in saving storages from puncturing. If the product or gases within a protected tank, however, become ignited, the walls present a hazard, preventing the efficient cooling of the tank side-plates. In addition, there is the ever-present danger of the walls collapsing as a result of cracking brought about by the internal heat.

This collapsing not only presents danger to personnel, but it has been

known, in cases where there has been burning product on the ground around a tank on fire, for the falling masonry to cause a wave of burning product spreading fire to other areas.

The very necessary precaution of keeping a close watch on the protection walls during an incident cannot be too strongly emphasized.

As has been shown in the foregoing descriptions, the earth covering of pipelines within areas that may be liable to product flooding, should tank disruption occur, served a dual purpose and prevented destruction by heat. In normal times, however, it is perhaps not good practice to bury product pipelines running within an installation as their condition cannot be seen and the presence of leaks goes undetected.

It is suggested, however, that the minimum amount of piping should be laid within tank compounds, all main pipe tracks being laid outside these areas.

Foam Application.

It has been stated that the standard rate of application to be aimed at is one gallon of foam per square foot of area per minute. Whilst this no doubt is an ideal, and should not be discounted, the impression which may be made, that petroleum products on fire should not be tackled until a sufficient number of appliances are assembled to give this rate, is to be deprecated.

Whilst it is possible when drawing up a protection scheme for an installation or refinery, to provide for an adequate number of foam appliances and material with ancillary machines, it is quite impossible to legislate for sufficient personnel being present in the event of an incident to operate such equipment as would give this rate, even on an average-size tank, say, of 85 ft diameter.

Speed, with collected reason and judgment, is the essential in dealing with the outbreak of fire involving petroleum products, and there is no hesitation in suggesting that as many appliances as it is possible to use with the people available at the time, should be put into use in the shortest possible time. This is where the training of installation staff is of importance, their operations subsequently being augmented by further assistance.

A further point on which comment should be made is the suggestion that in the event of more than one tank becoming ignited, only one should be tackled at a time, this, it being stated, as having come to light from experience gained. Again, it is suggested that all possible appliances should be made use of with all speed, and if circumstances permit, all tanks dealt with at the same time. The heat generated by burning products quickly causes the collapse of steel work and other structures which make extinguishing of the fire more difficult. This is particularly so in the case of fuel and lubricating oils where the temperature in the body of the oil rises progressively the longer it burns, which not only destroys the tank structure, but also destroys the foam when applied, reaching a condition where the product is liable to create a slop-over or boil-over.

In the early days of the war the Petroleum Board actively commenced to equip all above-ground tanks used for the storage of petrolum spirit with fixed foam inlets, the standard adopted being :—

Tanks from 200 tons up to 1000 tons capacity :—

1 No. 20 foam branch pipe.
1 No. 10 foam branch pipe.

Tanks above 1000 tons capacity :—

1 No. 20 foam branch pipe.
2 No. 10 foam branch pipes.

It was never intended that this standard would produce a sufficient volume in itself to be entirely effective, but it would provide a most desirable adjunct to portable equipment. Within the scope of the author's knowledge no tank fire has been extinguished with the sole use of fixed equipment.

Again, experience shows that if fire breaks out in a storage tank, the roof is invariably disrupted, followed soon after by the collapse of the upper tank plates with the consequent dislocation of fixed foam equipment. This is particularly so should the fire be preceded or followed by explosion.

Towards the end of 1940, the Petroleum Board gave consideration to the injection of foam through the base of storage tanks by means of the product pipeline system. As is well understood, the purpose of foam is to provide a covering of inert material over the surface of the liquid on fire in order to isolate it from the atmosphere and prevent the release of vapour which supports combustion. With the application of foam by any surface or top method, the foam must pass through the burning gases before reaching the oil surface, bringing about some destruction. In addition, the foam is caught in the up-draught above the fire and carried away, this being more noticeable when portable units are used. By the injection of foam through the base of tanks it was felt these disadvantages would be overcome as the foam would rise unhindered through the body of the oil.

Experiments both large and small proved the method to be effective, although there was and still is some criticism. On the result of these experiments the Petroleum Board decided to make provision on all tanks of capacity above 200 tons and used for storage of kerosines, fuel and lubricating oils, to permit of this method being used. The provision took the form of inserting a valved connection into the product pipeline at a convenient point not more than 300 ft away from the tank to be served, to which would be connected a converted No. 10 foam branch pipe. It was found that the standard branch pipe, when operated against a head pressure, exhausted a large volume of foam past the air skirt, and to overcome this a liner in the form of a venturi tube was inserted into the branch pipe.

At a later stage experiments, although only of a comparatively small scale, provided sufficient data on which a decision was made to extend the facility to tanks storing petroleum spirit and crudes, but in these cases each point had means for connecting two No. 10 converted branch pipes.

The method, although not perfect due to inefficiencies of the equipment, is open to improvement, but even at this stage is safe and reliable if operated under the guidance of one who knows the conditions of oil. A suggested line for research is the improvement of the branch pipe.

A paper was prepared in May 1942 for submission to the Government of the U.S.A. and the U.S. oil industry, on this subject, the outcome being that other large-scale trials were undertaken in America with considerable success.

Whilst making observations on fires, reference should be made to those which have at times occurred in tanks containing little or no product. These, as it may be gathered, have proved extremely difficult to deal with, consuming considerable quantities of fire-fighting material, invariably burning themselves out and sometimes ending in explosion. The difficulty is the large volume of gas to be consumed which, if a tank roof remains intact, has no access to atmosphere which would accelerate burning. So far there appears to be no efficient means of dealing with such outbreaks other than wet steam or CO_2 gas. It is not every oil installation which has steam laid on, and the volume of CO_2 gas required to deal with, say, a 10,000-ton tank would involve untold storage and handling difficulties.

Salvaging.

The salvage and removal of oil is a most essential part of all fire fighting at installations. In parallel with this it is very necessary at the time of fire for consideration to be given to the removal of the large volumes of water that accumulate in tank compounds from the cooling operations, and on which free product may be lying.

The Petroleum Board arranged for connections to be made in pipelines to which hoses could be connected and so reduce these flooded areas.

It is interesting to know, however, of the valuable use that can be made of a fire trailer pump. In one case a fire trailer pump ran continuously for four days and nights pumping petroleum spirit through ordinary 2½-in canvas fire hose. Some makes of pumps, however, are fitted with exhaust primers and it would, of course, be dangerous to use these for this product; likewise, it is unsatisfactory to use canvas rubber-lined hose.

General.

Petroleum products, as will be agreed, if handled and operated with due reverence and precaution—some more than others—are perfectly safe, but should a mishap occur, the resultant fire becomes a specialized risk. The guidance and decision for all operations, methods, and use of appliances, must, therefore, rest with the person who knows his installation or refinery and the product involved. Instances have occurred in the past where, with all good intent and enthusiasm, certain operations have unwittingly been the means of aggravating and prolonging the fire.

In conclusion, the author wishes to thank the Chairman and Management of the Petroleum Board for permission to publish this paper.

Discussion.

Mr H. Finch: Can the author give us some further information on the effectiveness of the American fog nozzles, and can he tell us how they work?

Mr Frederick P. Mills (Chief Officer, Durham and Northumberland Fire and Rescue Brigade): Have any experiments been conducted in the

use of mass carbon dioxide to lower the temperature of the contents of tanks? Would it be possible to introduce CO_2 into the base of the tanks?

MR J. H. HUTCHINSON (Messrs. I.C.I., Ltd.): I should like to question the advice to take away the fire-protection walls that are erected around tanks at a distance of 1 to 2 ft from the tank side plates. I should have thought it advisable to keep those curtain walls, not only to protect the fire-fighting personnel, but also to afford protection to near-by tanks.

COMMANDER K. N. HOARE (Manchester): Under the heading "Foam Application" the author refers to the application of foam at the rate of one gallon per square foot of area per minute as an ideal which should not be discounted, but he discounts the impression that petroleum products on fire should not be tackled until a sufficient number of appliances are assembled to give this rate. There is, however, the well-known law of "concentration of effort," and I feel that it is inadvisable to attempt to deal with fires unless you have sufficient material and equipment on the spot to carry on with the job effectively. In my view, to tackle a job with insufficient men and materials is a waste of effort, and I should like him to enlarge on that matter.

MR A. H. JOHNSTONE (Chief Regional Fire Officer, Bristol): I think most people will agree that the prescribed rate of foam application is something of an ideal which is not infrequently difficult of achievement when large-diameter tanks are involved—certainly in the earlier stages.

At the same time, it is useless to start operations until sufficient equipment and a reasonably adequate supply of compound is available to sustain a concentrated and effective rate of foam application.

I strongly disagree with extinguishing operations being commenced until these conditions are substantially satisfied, or likely to be met without appreciable delay. If you start by applying relatively small quantities of foam you achieve little or nothing, but may prejudice subsequent operations by vitiating your initial supplies of compound.

It is, of course, common ground that the attack should be opened at the earliest possible moment, but this should not be until a reasonably effective and continuing rate of application is ensured.

MR E. A. KIRBY (London): I was interested in the picture showing large quantities of foam on the roofs and walls of adjacent houses; very little foam found its way into the tank, as most of it was spread about by reason of the up-draught. I wonder whether that is tied up with the rate of application, whether, if the rate of application had been heavier, that difficulty would have been obviated.

MR E. E. CHANTER: I would like to add something about the rate of application of foam and the question of dealing with one tank at a time. I mentioned these points specifically in a lecture to the Institution of Fire Engineers in 1942.

In the northwest there was a particular oil fire which burned for many days. Foam compound and equipment were in very short supply at this time and a considerable quantity of foam was wasted and attacks on the

fire were spoiled by spasmodic application with too small an application rate. The success of foam is dependent upon the application rate being considerably in excess of destruction rate, and I would strongly recommend that sufficient foam and equipment should be available before an attack is made on a large oil fire.

In the event of several tanks being involved, unless there is adequate equipment to combat them all at the recognized application rate, it is better to fight them in turn according to their possible danger to the plant or installation generally.

On the question of building tank protection walls a few feet away from tanks, it is interesting to record a point which came to light during an inspection of the German tank protection measures. They were far behind us in their methods of protection and after installing hollow timber walls filled with sand and subsequently protected by Heraklith, they eventually protected some tanks with brick walls erected a few feet from the tanks. However, it appears that during intense fire raids, gas collected between the protection walls and the tanks, resulting in minor explosions and accompanied by jets of flame from manholes in the protection walls. It was reported that one particular incident of this nature resulted in twenty firemen being badly burned, two fatally—and I think this point should be borne in mind when reviewing the building of brick walls a few feet away from tanks.

COMMANDER HOARE: Reference has been made to base injection of foam and a certain amount of doubt has been expressed as to its effectiveness. Why is there doubt about it now, because surely we have had sufficient experience, both here and in America, to be able to say whether it is or is not effective?

MAJOR G. CHANTEAUD (Paris): I should be glad if the author would say more about underground storage tanks and the security provided by such tanks as compared with above-ground storage tanks.

MR J. W. MARTIN: In order to derive full value from the paper I think we should apply some of the lessons learned in the construction aspects of this subject. In particular I was very interested to learn of the measures taken during the war for the protection of the structural supports of tanks, overhead pipelines, etc, and I should think it would be recommended that those responsible for construction should adopt them as peace-time measures. The loss of strength when the steel is heated is very marked, and I can see no reason why fire-resisting insulation should not be adopted. It is done at refineries overseas on such things as butane spheres quite automatically; there are structural supports there carrying heavy loads, and I do not see any reason why it should not be done with the vertical members of all steel structures on oil installations.

Another important point is that, as noted in the paper, the two swing arms at Salt End provided very marked facility. I would deprecate the omission of swing arms, from the safety point of view.

Such matters should be observed by those concerned with the construction of installations.

MR MILLS: Has the author used chemical foam, as distinct from mechanical foam and if so has he any observations to make?

MR A. S. PRATTON: I should be interested to learn why rubber-lined hose is considered less satisfactory than un-lined hose in connexion with salvage pumping of spirit.

MR V. J. WILMOTH: The author states that, to his knowledge, no tank fires have been extinguished by the sole use of fixed equipment. Does that apply also to the powder or two-solution chemical installations which were a feature of pre-war practice?

MR E. W. REANNEY (Liverpool): Were any of the tanks involved fitted with the Wiggins roof, and have you experience of tanks with Wiggins roofs?

MR H. E. F. PRACY: It has occurred to me from time to time that, if we are not at all certain whether base foam injections are effective, why not apply the foam through the swing arm, and so get on to the top of the oil without going up the outside of the tank?

MR LANCASHIRE, replying to the discussion, said: The first question concerned the American fog nozzles, and I am afraid that I have no data at all other than that published by the manufacturers. But I have seen the nozzles in use, both actually and experimentally, and my own view is that they have limited application. They were used by the Americans at Falmouth; whilst they were effective when in operation, the moment they were shut off everything became alight again. The area concerned was such that it was quite impossible to accumulate sufficient nozzles to cover the whole of it at one time. Their particular value, I feel, is in cooling; their use involves the application of "atomised water," if I may be allowed to use that term, such water being readily converted to steam and giving a greater cooling effect than does solid water.

Mr Mills asked whether carbon dioxide has been used by introducing it into the base of tanks. My answer is "no," and I have no knowledge that it has been tried anywhere.

Thirdly, there was a question concerning the demolition of curtain walls; and I thank Mr Chanter for quoting his experience in Germany. This matter is hardly one for me, for it involves higher authority. However, we must realize that operationally it is quite impossible to know what is happening to the tanks at the back of these walls, and for that reason the walls are being demolished. Likewise, as I have stated in the paper, it is quite impossible to see what is happening to buried pipelines. In some cases where protection walls have been demolished it has been found that the tanks are not in too good a condition, whereas others are in very good condition. All I can say is that it is the policy of the industry generally to demolish the brick walls.

MR HUTCHINSON: I am speaking for I.C.I., Billingham; we have three walls at least 2 ft away from the tank sides, and we have been able to get at the tanks to paint them. From this point of view there seems no reason why we should remove them; but I should like the opinion of fire

fighters concerning the use of the fire walls as a fire protection. We know that they collapse, but we know also that they often stand up. The film showed an incident at Manchester, where, as the result of a fire, certain unprotected overhead storage tanks dropped to the ground, whereas near-by brick protection walls remained standing and successfully protected ordinary storage tanks. I should have thought that, from the point of view of the protection of near-by tanks, it would be advisable to leave the curtain walls. However, I am merely asking advice.

MR LANCASHIRE: I should imagine that one difficulty during fire is in the application of water as a cooling medium to tanks so protected; it seems quite impossible to get at a tank having a wall around it. Probably, however, some of the firemen may have views which will help Mr Hutchinson.

THE CHAIRMAN: Are there any Fire Officers here who could make some comments or quote their experience on this matter?

A SPEAKER: I think we have to bear in mind the thickness of the walls. They were built in fairly thin brickwork, and it was not long before they broke down. I would suggest that probably, if we constructed 9-in or 15-in brick walls, we might arrive at what we want, for the purpose of providing a brick surround to a tank.

THE CHAIRMAN: The query is whether such brick walls will hinder or facilitate fire-fighting in normal times, not wartime. It would appear that at Barton the brick walls were not affected by the bombs, and that they prevented product escaping into the compound from one particular tank.

MR HUTCHINSON: In our case the walls are from 13½-in thick, and they are very largely reinforced. Should we remove them? I take the view that we should not.

COMMANDER J. E. FARRELL (Swansea): I should like the walls to remain if it were my responsibility in that particular area, but surely this is a matter for the Petroleum Board. I should say that the retention of the walls would help rather than hinder us.

A SPEAKER: I think it is right that the walls should be removed, whether they are adjacent to a fuel tank or some distance from it. Cooling must be an essential part of fire-fighting operations in connexion with all tank fires.

MR R. J. WARD: My experience has been gained abroad, and there, of course, the bunds are very much farther away and are not so high as here. It seems to me that we might overcome this cooling difficulty by means of a system of sprinklers at points around the roof, in order to keep down the temperature of a tank by sprinkling its sides with water. On the Russian field we had such a system.

THE CHAIRMAN: At the tops of the tanks, not the sides?

MR WARD: Yes.

THE CHAIRMAN: Have you had experience of actual fires in Russia?

MR WARD: Yes, there were many fires there during the first world war, the fires being started by sabotage. The only trouble was that we were using salt water instead of fresh water, which latter is better; the nozzles became choked with salt from the salt water. But by using fresh water through sprinklers it should be possible to reduce temperature.

What I cannot understand is the closeness of the curtain walls to the tanks, as shown by the author's photographs; one speaker has suggested that they might be placed farther away.

MR LANCASHIRE: The point did arise as to whether the walls should be built flush to the tank side or some distance away. But I think you will realize that tanks in this country are very much closer together than probably they are overseas, and in some cases there is a distance of only a few feet between tanks. It was decided to build the walls flush to the tank sides as affording the best protection. But in the case mentioned by Mr Hutchinson I believe the decision to place the walls away from the tanks was due to the unstable condition of the ground. In similar cases the Board also built walls away from the tanks, but the method generally adopted was to build them flush up to the tanks.

The use of fixed sprinkler pipes is adopted in a number of instances in this country. But, as I mentioned in my paper, fixtures on tanks which catch fire or which are affected by fire do not remain intact for very long, and therefore, one has always to fall back on to something portable. Again, if one puts a sprinkler on a tank it must be of fairly large dimensions, and that results in the consumption of considerable quantities of water.

MR WARD: Is it worth while attempting to save a particular tank which is on fire? It is better I think to isolate and keep cool neighbouring tanks which are not in actual contact with the fire.

MR LANCASHIRE: I think it most certainly is worth while attempting to save a tank which is on fire. The cooling of near-by tanks is essential and should be operated as quickly as possible.

MR FARRELL: One reason why I was so definite in my opinion about retaining the walls is that if they are away from the tanks the question of cooling does not arise so acutely as it would if the tanks were entirely unprotected.

MR S. H. CLARK: We have not had practical experience in our Division of the effect of walls on the tanks; but in the discussions there the suggestion has been made several times that we might compromise by taking off the top part of the walls, which would allow the tanks to be cooled and would at the same time afford a certain amount of protection.

MR HUTCHINSON: Drenchers have been used on the tops of storage tanks at Billingham and we found them useful for cooling. But we found also that the wind had a very bad effect; the water from the drenchers was driven to the far side of the tanks, so that we did not attain more than 30 or 40 per cent coverage over each tank. That was the effect of a normal wind.

THE CHAIRMAN: Are you satisfied by the observations made as to whether walls should remain or be taken away?

MR HUTCHINSON: We shall have to make our own decision after hearing the discussion.

MAJOR CHANTEAUD: I think that walls erected at some distance from a tank provide, not only protection to the tank itself, but also the capacity to retain the liquid content if the walls of the tank itself are punctured. I suppose that these walls are much lower than the tank itself, in which case I do not see how they can prevent the cooling of the tank or, in the event of the tank being punctured, how they can prevent the extinguishing of the fire by ordinary foam appliances.

MR LANCASHIRE: Probably we have not made ourselves clear. These walls in themselves are not liquid-tight, so that they do not provide the means of forming a reservoir between the tank and the walls; they have openings to give access to tank-side manholes.

MAJOR CHANTEAUD: In France it was compulsory during the war to build these walls around the tanks and to make them liquid-tight, so that they would retain any liquid which escaped from the tanks themselves and so prevent it spreading the fire.

MR LANCASHIRE: You are referring to tank area bund walls. We have been discussing the brick walls around the tanks themselves.

MAJOR CHANTEAUD: I quite understood. They are not the same?

THE CHAIRMAN: Do we understand you to say that in France you built the walls around the tanks to act as retainers as well?

MAJOR CHANTEAUD: Yes.

MR E. THORNTON: We put our walls close against the tank because we felt that as a protection a wall of brick and concrete, supported by the weight of the tank, would withstand blast better than would a wall 40-ft high built just free of the tank. Was there any experience in France of what happens to a wall built away from a tank when subjected to blast from a near miss?

MAJOR CHANTEAUD: Yes. Many times, in the suburbs of Paris, they seemed to withstand the blast quite well, if they were not very high above the ground.

MR THORNTON: Were they 40-ft high?

MAJOR CHANTEAUD: No; they were about 7 metres (28-ft) high.

MR A. F. GOODWIN: At the installation I am in charge of there are twenty-nine tanks of capacities from 62,500 gallons to 625,000 gallons used solely for the storage of lubricating oils. When the curtain walls were built, provision was made for a space of 1½-in between them and the shell of the tanks.

At first I was in favour of retaining these walls, as during the winter

since they have been erected, uncoiled tanks were certainly less affected by the cold weather and pumping out was much easier than previously. After 1945, however, a number of holes were cut in the brickwork to ascertain the condition of the tanks and it was then found that during construction the cement had slopped over, and about every ten courses there was a solid belt around the tanks.

When this belt was chipped away, the shell showed signs of corrosion, and as this will increase, it is now considered advisable for the walls to be removed.

MR LANCASHIRE: The next question concerned the loss of foam, due to up-draught, and I think the speaker concerned queried whether that was tied up with the rate of application. There may be something in that; I do not know. All I can state is the fact, which I have seen on many occasions, that, to a degree depending on the velocity of the wind, quite a considerable quantity of foam is carried away. The particular incident shown on the screen, where the foam formed a covering on the roofs of the nearby cottages, was one in which chemical foam was used; something like 4000 lb of powder being consumed.

Another question concerned the use of appliances, and I agree that I advocated immediate attack with all available appliances. I still stand by that advocacy, although I know that many here are not in agreement with me. It has been pointed out that there is such a thing as concentrated effort, and I agree entirely. At the same time, I suggest that there is such a thing as first aid. One cannot lay down a hard and fast rule to suit all cases; but in many cases the people available at the works at the time a fire has occurred have marshalled their forces and appliances and have put the fire out before assistance has arrived. If they had waited until the requisite appliances could be marshalled to give the prescribed rate of application they would probably have been faced with a much larger fire. However, the point is debatable; but I recommend immediate attack.

The next question also referred to foam application, and Mr Chanter mentioned an incident which lasted several days. I gained the impression that it was not until the end of that period that a sufficient quantity of material and appliances and personnel were marshalled to deal with the fire. Surely there is something wrong if it takes so long to accumulate material and appliances and personnel; I do suggest that in these days it is not necessary for an oil storage tank fire to last for so long. With the modern appliances and equipment laid on in the industry and in the National Fire Service, the extinguishing of such a fire, particularly in peace-time conditions, where we are not faced with, say, forty tanks burning at once, should be merely a matter of hours.

It was stated that apparently I have some doubt about the efficacy of base injection. I am sorry if I gave that impression, for I did not intend to do so. I think base injection is very effective, as has been proved by the experiments carried out in the early days. At the same time, I suggest that it can be improved and, as I mentioned in the paper, I feel the line of research should be through the appliance. The appliance at present in use is an adaptation or conversion of an instrument basically designed as a

portable appliance. The objection to the method, I think, comes from other quarters, and you will probably wish to discuss it further, following the papers by Dr Burgoyne and Dr Clark.

The next enquiry concerned the difference in the degree of protection as between underground and above-ground storage tanks. Commercially, I do not think there is much in it; but I do say that, should a fire occur in an underground tank containing very little product, it presents a far more difficult problem to deal with than would a fire in an above-ground tank containing an equal amount of product. One has to deal with something like a hole in the ground, which one cannot get at; the tank cannot be cooled, and all that can be done is to project the foam downwards. In some instances provision has been made to inject foam through the product lines. But again there is the difficulty that the valves are also below ground, and that means that people have to enter the chambers to operate the valves. However, I think that generally it is a question of cost. It is much cheaper to build an above-ground tank, and one can deal more easily with the maintenance of such storage. I think there have been only two fires in underground tanks during the past few years. One or two other underground tanks were damaged, but fires did not result; on one occasion a fire occurred in such a tank containing very little product, and on the other occasion the fire was due probably to the particular point of explosion.

With regard to adopting measures to protect steelwork supporting overhead structures and pipelines, it has been suggested that we could learn from experience and maintain such protection measures as a general practice; I agree entirely. Likewise it is probable that designers may gather other interesting points for use when they are considering the construction of storage tanks.

Coming to the point regarding the continued use of swing arms, I must agree. I definitely prefer operationally the use of swing arms; not only are they of assistance in blending, but they are of untold value in other operational matters, as when one wishes to remove product from a tank, particularly working downwards from the surface. However, as I have said, it is a matter in connexion with which designers might gather some points from our past experience.

In reply to Mr Mills, I must say that I have had very little experience of chemical foam; practically all my experience has been with mechanical foam. But probably there is someone present who may be able to give some advice.

THE CHAIRMAN : Is there anyone here, other than a manufacturer of foam of one type or the other, who could speak on the matter?

MR E. THORNTON : There is no question about its effectiveness, as compared with mechanical foam, once it is on the fire. But it is a question of getting it there, and of how quickly you can get it there with the aid of the manpower available, and so on.

MR LANCASHIRE : The next questioner asked why I did not recommend the use of rubber-lined hose for salvaged products. I was dealing only with petroleum products, which do not go very well with rubber. It is

quite natural that, if one is salvaging several tons of petroleum spirit by means of a trailer pump through rubber-lined hose, the rubber lining will not last very long; it will eventually come through in a solid mass and will jam up in the pump. For that reason I did not recommend the use of rubber-lined hose; ordinary canvas hose will do the work very satisfactorily in an emergency.

The next question was whether there has been any experience of fires in tanks fitted with pontoon roofs. Generally the fires on pontoon-roofed tanks have been brought about from adjoining tank fires; in such cases the canvas seal has ignited and there has been merely a periphery fire about that seal, it being extinguished very easily by the use of portable extinguishers or a small foam branch pipe. In one case, I think, a pontoon roof was directly damaged and it collapsed, *i.e.*, it sank below the product, and the vertical plates collapsed inwards on top of the roof. Beyond that I am afraid I cannot give any more data.

Reference was made by Mr Pracy to the apparent doubt concerning the efficacy of base foam injection, and again I say that it is most effective. The application of foam by means of fittings up the side of the tanks is comparable with top foam inlets, and there we are up against the problem of the rapid destruction of anything so fixed, particularly at the top.

MR PRACY: I was talking of putting in the foam through the swing arms.

MR LANCASHIRE: That is probably a useful method, if there is a swing arm.

A SPEAKER: And if the wire is still there!

MR LANCASHIRE: What I should like to see on future designs is a permanent connexion on the side of the tanks, not part and parcel of any product connexion, but provided merely for foam application through a line which may be led from some convenient point. An automatic valve, reflux valve or non-return valve might be incorporated which would operate automatically by the pressure of foam, so that it would be unnecessary for personnel to go to the tank side to open a main valve. That is just a personal expression of opinion.

Vote of Thanks.

MR A. B. CRAIG (Principal Fire Staff Officer, N.F.S. in Scotland), proposing the thanks of the meeting to Mr Lancashire for his paper, said: I cannot recollect any previous opportunity such as this for members of our Institution to enter into discussion with another body which has an interest in our work on this particular subject. Mr Lancashire and I are not exactly strangers; I remember that in 1943 we had a problem which recalls to my mind his general remarks at the end of the paper. He states there that the guidance and decision for all operations, methods and use of appliance must rest with the person who knows his installation or refinery and the product involved. The point arose in Scotland, and I venture to suggest that it arises again here. I do not think that the decision for all operations, methods, and use of appliances must rest with the person who

knows his installation. It is my view that this is another case for the general collaboration of the staff of the establishment and the Fire Officer who will be called in to deal with an emergency, but that the final decision lies with the Fire Officer; it is his job. I do not make that statement in a spirit of carping criticism. The point has occurred to me, and I do not doubt that my suggestion will be supported in the Regions; I see no reason why the Institute of Petroleum and the Institution of Fire Engineers cannot get together in their branches in the provinces and talk over the sort of things we have talked over here to-day. That will be to our mutual benefit; I know that Mr Nisbet, our I.F.E. Secretary in Scotland, has already made a tentative approach to Mr Thornton as to date and time, and I hope we shall have a smaller edition of this meeting, because it engenders thought, not only on what has been, but also on what might be in the future. We are not concerned only to learn the lessons of the war; let us continue to learn one from the other, apply our knowledge to mutual advantage, so that at any time we can say that the collaboration between these two bodies has been extremely successful.

You, Mr Lancashire, have assisted the first movement in this direction by presenting your paper and by dealing so admirably with the questions raised in the discussion. It is already clear that there is no common agreement; some say " aye " and some say " no," and it will always be so. Controversy produces the final solution. I thank you very much indeed, on behalf of all of us here, for your paper, so splendidly presented.

MR MILLS, seconding, said: We have had a most interesting paper, and the author is to be congratulated on its preparation.

With regard to the problem of keeping down the temperature in tanks, why not have a tank built very much on the lines of the thermos flask, having two metal walls, so that between the two walls can be introduced large quantities of carbon dioxide gas to maintain a low temperature of the contents.

Among the photographs of tank installations we have seen to-day I noticed that some are built on hillsides. That disturbed me particularly, because should the tanks burst, the contents run down the hillsides with damage to life and property. It seems to me that the tanks should be built below the ground level, in areas which can retain the contents in the event of a burst.

It is my pleasant duty to second the vote of thanks to Mr Lancashire, and I do so with very great pleasure.

(The vote of thanks was carried with acclamation.)

MR LANCASHIRE, responding, said: I must thank you all very much indeed for the way in which you have received the results of my effort; it is very gratifying to know that the paper has given you something to think about.

I can recall the incident to which Mr Craig has referred. When writing a paper one has not the benefit of numerous criticisms; but now I feel that I might have emphasized the importance of co-operation with the professional firemen, for I agree heartily on that matter. I do not wish to labour the point, but I think the professional firemen must be guided to a

very considerable extent by the people in charge of the works, because of the particular product that has to be dealt with there. At the same time, I entirely agree with whole-hearted and open co-operation and collaboration; I hope this occasion is by no means the end of co-operation and collaboration between the professional fire services, the Institution of Fire Engineers and the petroleum industry through the Institute of Petroleum.

MR A. FRANK DABELL (written contribution): I regret that I was unable to pay tribute personally to Mr Lancashire for the care devoted to his records and to express agreement with his conclusions.

Uncertainty would appear to still prevail as to the reason for or the absence of ignition following bombing attacks.

In previous papers Prof Garner suggested tentatively that the reason for ignition was the attainment of fire-point temperature; Mr Wilmoth suggested chemical origin; Major Cadman considered that it was due to the heating of a certain section of the oil to a temperature above that of self-ignition; whilst Mr Lancashire now reports spirit released through punctures being fired, presumably, by hot fragments.

I think it conceivable that the origin does not lie at the point of contact between liquid and vapour but at some point distant from the tank where a critical air/vapour mixture exists and is there fired by the bomb explosion.

This would operate similarly to lightning (though in reverse direction) which, often attracted to tank forms by lightning conductors, must pass through mixtures of varying air/vapour proportions and encounter one of a readily combustible nature.

I am surprised to note from the records the absence of the use of the simplest, cheapest, and most efficient method of extinction—passage through pipes or their equivalent. It is a mistake to imagine that this treatment calls for complicated fire-traps. Any old straight or contorted pipe will serve the purpose, provided it is sufficiently long enough to prevent reignition by flash-back.

With reference to the reported difficulty and danger in dealing with tanks, with roofs intact, containing vapour but little or no liquid, I have to repeat my advice that safety lies with roof funnels. These, fitted with flame arrestors and/or breathing diaphragms permit vapour released to burn with impunity. Where gas is at liberty safety is assured only when that gas is burning.

It is to be hoped that now, in case of conflagration, there will be no call for undue haste in extinction with its ensuing dangers, or for the maintenance of tank curtains blinding the state of tanks, etc. We should, however, carry forward such lessons as the value of speed in the initial stages of the fire with the necessity of more leisurely judgment in the latter stages; the call for protection of tank contents from abnormal radiating heat; and more forethought in the arrangement of pipelines, etc.

To-day, a glance at the close spacing in small tank forms, many located near main railways, will show that if one tank is fired all must follow.

Incidentally, the use of the word inflammable in technical papers is to be deprecated. Its illogical interpretation in the United Kingdom is misleading to American readers.

DR J. H. BURGOYNE and MR L. L. KATAN (written contribution): We have made experiments in which solid carbon dioxide was thrown into a tank of oil on fire. The lumps sank to the bottom where they continued to evaporate and thus produced the effect envisaged by Mr Mills. The result was the same as when air was bubbled through the oil: if the oil was not too volatile or too viscous the fire was extinguished by the stirring effect dealt with in our paper on "Fires in Open Tanks". It was evident that the quantity of gas required to cause this effect was so small that its ability to promote combustion was of little consequence and carbon dioxide or air could be used indiscriminately as the stirring agent.

EVENING SESSION.

THE CHAIRMAN (Mr E. Thornton), inviting Drs Burgoyne and Katan to present their paper, said: The paper deals with the behaviour of a representative selection of petroleum products when burnt in open-topped cylindrical vessels. I agree that the work has not proceeded much beyond the scale of the 9-ft diameter tank; but I ask you to consider very seriously the implications of the paper, which covers work carried out over a period of two years.

The following paper was then presented by Dr Burgoyne, and illustrated by means of a series of cinematograph films showing successive stages of some of the experiments dealt with in the paper.

FIRES IN OPEN TANKS OF PETROLEUM PRODUCTS: SOME FUNDAMENTAL ASPECTS.

By J. H. BURGOYNE, D.Sc., Ph.D., D.I.C., and L. L. KATAN, A.R.C.S., B.Sc.

SUMMARY.

Observations have been made upon the behaviour of a representative selection of petroleum products when burnt in open-topped cylindrical vessels. It has been shown that many refined oils burn in such a way that virtually all the fractions are removed layer by layer leaving little or no residue of any kind, and the bulk of the oil, apart from a comparatively shallow layer near the surface, is not at all affected by the fire. Crude and residual oils, and motor spirit have, however, been found to burn in such a way that only the lighter fractions are removed layer by layer and a hot residue steadily accumulates, floating on the unaffected oil.

The hot residue, especially if its temperature exceeds 100° C (as it does with crudes and fuel oils), constitutes a hazard particularly when extinction of the fire by the use of water in some form is attempted. It is suggested that in these circumstances the body of cold oil below may be used to cool the hot residue and thus remove the hazard. Some ways of doing this are examined and it is shown that the method not only removes much of the danger but may be extended, within limitations that are defined, to the complete extinction of the fire without the use of auxiliary measures, both in oils that do and do not form the hot residue during burning.

GENERAL INTRODUCTION.

APPROACH to the problems associated with oil-tank fires has hitherto been mainly on practical lines. It must be granted, however, that only limited advances are possible without a full assessment of the underlying character

of the phenomena concerned. The investigations described in this paper were undertaken to elucidate basic aspects of the burning of petroleum products in bulk, particular attention being paid to some of those grades at present in use in Great Britain.

A general exposition of the temperature changes occurring beneath the surface of burning oils was given more than twenty years ago by Hall (*Mech. Eng.*, 1925, **47**, 540). As a result of 100- and 350-gal experiments, only three of which are recorded in detail in Hall's published work, the phenomenon of the " heat-wave " was recognized and associated with oils containing appreciable proportions of heavy ends : it did not usually appear with refined oils. Hall showed that the " hot zone " consisted of an accumulating hot residue left by the distillation and burning of the lighter fractions, which was capable of floating on top of the unaffected oil. Downward heat transfer occurred due to the falling through the hot zone of heavy ends left by a final distillation of the hot zone oil at the surface itself. As a result, distillation occurred at the interface of the hot and cold oils and led to a continual diminution in the amount of the latter by the removal of light ends which bubbled up through the hot zone to feed the flames.

The occurrence of " boilover " was associated by Hall primarily with the impact of the " heat-wave " on water at the bottom of the tank, but he found that the occurrence did not take a violent form unless the oil, or at least the sediment at the bottom of the tank, was of a viscous nature and able to form a froth with the steam rising through it. He suggested that the rate of progress of the " heat-wave " depended on such a variety of factors that its value could not be predicted in a given case, and recommended the use of temperature-indicating paint to anticipate the occurrence of boilover.

Subsequently, this investigation was continued, it is believed under the auspices of the Standard Oil Company of California, and numerous measurements of the rate of progress of the " heat-wave " appear to have been made in large-scale tests. Details of these experiments do not seem to have been published, but the figures given in Table I were put out by the American Petroleum Institute (Fire Protection in Refineries, N.F.P.A., 1941) and have been widely quoted.

TABLE I.

Heat-wave Rates (American Petroleum Institute).

Kind of oil.	Heat-wave rate (in/hr).	Burning rate (in/hr).
Light crude oil (25 deg. API and above) :		
Dry (under 0·3% water)	15–35	4–18
Wet (over 0·3% water)	17–50	4–18
Heavy crude and fuel oil :		
Dry (under 0·3% water)	3–20	3–5
Wet (over 0·3% water)	12–50	3–5
Tops	9–14	6–10
Kerosine	None	5–8
Gasoline	None	6–12
Casinghead gasoline	None	15–25

The investigation now to be described necessarily began by going over some of the ground covered by Hall, although different grades of oil have

been used. A re-examination of the burning behaviour, described in Part I of this paper, has led to an amplification of Hall's conclusions and to a clearer definition of the problems besetting the firefighter at oil-tank fires. At the same time, ways in which these difficulties may be overcome with diminished hazard have been developed and are discussed in Part II.

Part I.—The Burning Behaviour of Petroleum Products.

Apparatus and Method of Experiment.

In general, the method of experiment was to burn standard grades of oil in open-topped (vertical) cylindrical tanks. All the experiments were conducted in the open air. Detailed observations of temperature changes below the liquid surface were made by means of submerged thermocouples. Readings were also taken in the vapour and flames, but undue significance is not to be attached to them. In addition, temperatures at various points in the tank walls were observed and some measurements of radiation from the flames were made. The gross rate of loss of oil was measured, generally by means of a manometer connected to the base of the tank. Arrangements were available for withdrawing oil samples from certain points in the tank at any time during an experiment.

Most of the experiments were done in two tanks which will be referred to, for brevity, as "small" and "large." The small tank was 22 in in diameter and about 40 in deep, having a full capacity of 55 gals. The large tank had a diameter of 9 ft and was 16 ft 4 in deep, having a full capacity of about 6500 gal. The small tank was used for most of the work, it being of convenient size for an exploratory investigation. The large tank was, however, used for a programme of experiments on fuel oil, mainly to examine methods of controlling the fire (see Part II). For brevity, details of the tanks and equipment and of the safety precautions are omitted from the present account. Except where otherwise indicated it can be assumed that the experiments referred to were conducted in the small tank. In either case, quantitative results refer primarily to the conditions under which they were derived, and extreme caution should be exercised in applying them to other conditions.

Results.

Hot zone formation.

It was known at the outset that some oils do, and some do not, form a "hot zone" during burning. This appeared to provide a basis for classification and it is convenient to make use of it in presenting and discussing the results obtained. In Table II the allocation of the grades examined, as revealed by our experiments, is shown, together with an indication of the properties of the oils used.

While all the oils appearing in the non-hot-zone-forming class are distillates the appearance of pool motor spirit in the hot-zone-forming class demonstrates that the converse is untrue. As will be seen, however, in subsequent sections, there are differences of behaviour amongst the hot-zone-forming oils which have an important bearing on practical fire-

TABLE II.

Clasifications of Grades Based on Hot-zone Formation.

Form no hot-zone.			Form hot-zone.		
	Sp. gr. at 60° F.	V.R.I. at 100° F. (sec.).		Sp. gr. at 60° F.	V.R.I. at 100° F. (sec.).
Pure benzol	0·882	—	Iranian crudes	0·861	58 [2]
Pool white	0·801	—	South-west Texas crudes	0·827	—
Pool burning oil	0·8085	—	British (Eakring) crudes	0·872	141
Pool vaporizing oil	0·823	—	Pool motor spirit (leaded)	0·745–9	—
Pool gas oil	0·849	34	Pool motor spirit (unleaded)	0·742	—
Pool marine diesel oil	0·910	45	Pool fuel oil	0·941–3	180–200
Pool transformer oil	0·87–8	—	Pool heavy fuel oil	0·965	504
		K.V.C.S. at 100° F.	Pool marine fuel oil	0·985	2000
Pool lubricating oil, grade 3	0·919	20·18			
Pool lubricating oil, grade 8	0·930	109·25			
Pool lubricating oil, grade 17	0·917	719·44			
Pool lubricating oil, grade 20	0·941	1389·0 [1]			

[1] At 60° F. [2] At 70° F.

fighting considerations, and it will be convenient generally to discuss them in three groups—fuel oils, crudes, and motor spirit.

Non-hot-zone-forming oils.

Among the non-hot-zone-forming oils Pool gas oil has been examined in most detail, and in discussing the results this grade will be considered primarily, while results for the other oils of the class will be summarized as briefly as possible.

A typical record of measurements made during the burning of Pool gas oil is shown in Fig. 1. The upper diagram illustrates temperature changes at fixed levels in the oil, plotted on a time base, and the lower diagram shows the change of pressure at the bottom of the tank, due to loss of oil by burning, plotted on the same base. In the temperature diagram, height above the tank bottom is marked on the left-hand ordinate, on which the positions of thermocouples are indicated. The axis of each thermocouple is employed as the time ordinate for corresponding temperature records plotted according to scales shown on the right-hand side.

In the experiment referred to in Fig. 1, a damp asbestos blanket was drawn over the tank after 61 min burning and the fire instantly extinguished. As soon as the blanket could be removed without re-ignition, the level of the oil surface was noted. Since the manometer (registering *weight* of oil) showed a steady burning rate, and the proportion of oil subject to heating was small, it was concluded that to assume a linear fall of the surface during

the fire was justified. Since the initial oil level had been noted the position of the surface throughout the experiment could be interpolated as shown in Fig. 1.

The rate of fall of the surface thus indicated was 5·28 in/hr. That calculated from the manometer record neglecting expansion of the oil due to heating was 5·37 in/hr. The agreement between the two figures is within the probable experimental error and justifies the assumption that expansion of an oil of this type during burning is inappreciable.

Thermocouple records at one-inch intervals of depth show that when conditions had become steady (after about 20 min burning) appreciable

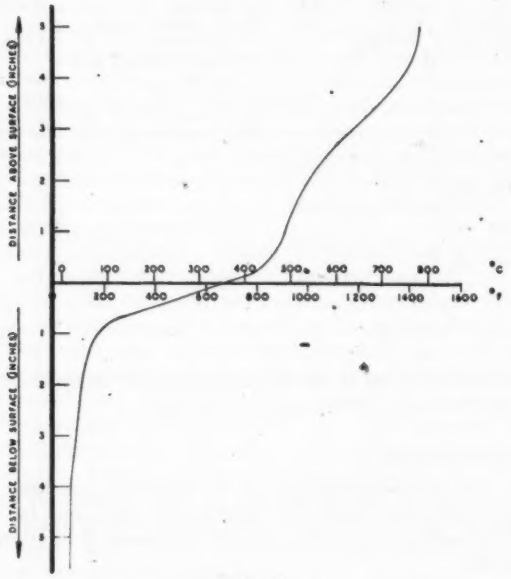

DISTANCE ABOVE SURFACE (INCHES)
DISTANCE BELOW SURFACE (INCHES)
0 100 200 300 400 500 600 700 800 °C
200 400 600 800 1000 1200 1400 1600 °F

FIG. 2.

POOL GAS OIL—TEMPERATURE DISTRIBUTION NEAR SURFACE AFTER BURNING 45 MIN.

heating of the oil did not penetrate more than about 2 in below the surface and that this state of affairs altered very little with time. In Fig. 2 the distribution of temperature in the neighbourhood of the surface during the "steady" period (actually after 45 min burning) is shown. In considering this and similar curves it must be borne in mind that the temperature readings were taken with horizontal thermocouples having a diameter of $\frac{1}{4}$ in: the effective position of each thermocouple was assumed to be on its axis for the purpose of plotting temperatures.

The mean of temperature readings of all the thermocouples at the instant at which each in turn intersected the surface was 354° C. An A.S.T.M. distillation on a sample of the oil used gave 97 per cent distilled at this temperature. Thus the surface temperature appeared to be very close to

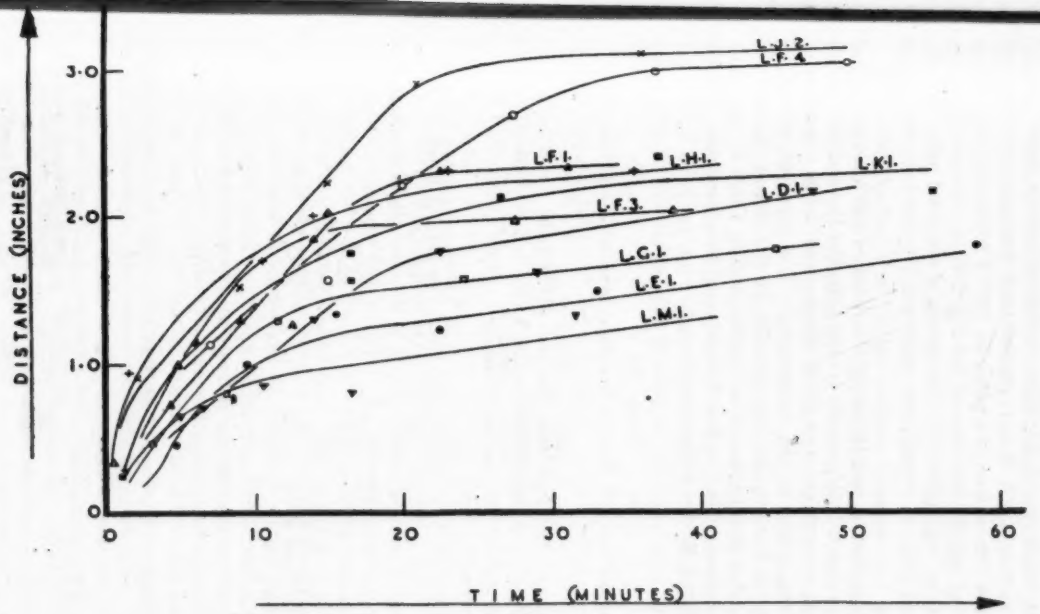


FIG. 3.

MISCELLANEOUS REFINED OILS—VARIATION WITH TIME OF DEPTH BELOW SURFACE OF 100° F PLANE.

KEY.

- ▼ L.D.1. Pool lubricating oil, grade 8.
- ● L.E.1. Pool burning oil.
- ▲ L.F.1. Pool gas oil.
- △ L.F.3. Pool gas oil.
- ○ L.F.4. Pool gas oil.
- □ L.G.1. Pool white spirit.
- \+ L.H.1. Pool vaporizing oil.
- × L.J.2. Pool lubricating oil, grade 3.
- ■ L.K.1. Pool lubricating oil, grade 20.
- ▽ L.M.1. Pure benzol.

the F.B.P. of the oil, a conclusion that was confirmed by further experiment.

In none of the other oils of this class examined was the penetration of heat below the surface much, if any, greater than with gas oil. In Fig. 3 the distance below the surface of a plane at 100° F (depicting appreciable heating) is plotted against the time of burning for the various oils. It is seen that a state of negligible heat absorption is achieved after 10 to 20 mins burning and that the equilibrium penetration varies between 1 and 3 in on this scale.

In view of these results, and following the detailed examination of Pool gas oil, it was considered permissible to compute the locus of the surface level in all the experiments from an initial direct observation, together with weight changes registered by the manometer. The observed rate of fall of surface computed from weight loss is shown for the various oils in Table III in which weather conditions are also noted, and in Table IV, the mean recorded temperatures of the surface thus located are correlated with the corresponding A.S.T.M. distillation results.

TABLE III.

Mean Rates of Burning and Weather Conditions (Non-hot-zone-forming Oils).

Grade.	Rate fall surface in/hr cold oil.	Wind (estimated Beaufort scale).	Rain.
Pure benzol	10·5	1	None
Pool white spirit	8·1	3–5	Occasional drizzle
Pool burning oil	6·4	1–2	Showers
Pool gas oil (i)	5·5	1–3	Slight drizzle in first 30 min
Pool gas oil (ii)	5·5	0–1	None
Pool gas oil (iii)	5·3	0–1	None
Pool vaporizing oil	4·8	2–3	None
Pool gas oil (iv)	4·2	2	None
Pool lubricating oil, grade 20	3·9	2–3	First 5 min
Pool lubricating oil, grade 8	3·9 *	3	None
Pool lubricating oil, grade 3	3·1	3–4	None

* Steady value reached after 20 min; normally the rate was constant almost from the beginning.

TABLE IV.

Mean Surface Temperatures and A.S.T.M. Distillation Data (Non-hot-zone-forming Oils).

Grade of oil.	Mean surface temperature (° C.).	Per cent distilled analytically at mean surface temperature.
Pure benzol	93	98
Pool white spirit	206	93
Pool vaporizing oil	321	100
Pool burning oil	326	100
Pool gas oil (1)	366	100
Pool gas oil (2)	354	97
Pool gas oil (3)	358	98

The results shown in Table IV confirm the correspondence of the mean surface temperature with the F.B.P. In the cases of the Pool lubricating oils, for which A.S.T.M. distillations were not carried out, the mean surface temperatures were as follows :—

Grade 3	371° C.
„ 8	325
„ 20	586

The correspondence of mean surface temperature with the F.B.P. suggests that in this type of oil the complete range of fractions is taken off and burned in each succeeding layer of oil as the surface falls in the course of the fire. That the process leaves no appreciable residue is further demonstrated by the fact that in no case has it been possible to detect any change of composition in the underlying oil during, or as a result of, burning. Reverting to Fig. 2, it is seen that in gas oil the I.B.P. (150° C) is reached about ½ in below the surface. In the short distance between this plane and the surface itself we can picture the whole range of distillation occurring, a given layer completing the process in 5–6 min (rate of fall of surface 5½ in/hr).

Hot-zone Forming Oils.

(1) *Fuel Oils.* Under this heading, attention has been directed almost exclusively to Pool fuel oil. Experiments with the heavier grades have sufficed to show, however, that their burning behaviours are qualitatively similar.

Surface Temperature. In Fig. 4 the results of a typical experiment of moderate duration with Pool fuel oil are illustrated. After 62 min burning the fire was extinguished with a damp asbestos blanket in order that a direct reading of level might be obtained. By interpolating between this and the initial reading (the loss of weight relationship being linear) the locus of the surface as shown in Fig. 4 was derived. The temperature distribution in the neighbourhood of the surface after 45 min burning is plotted in Fig. 5 from which it is seen that there was some evidence of a temperature gradient over a narrow surface zone in the liquid phase. The literal indicated value of 0·1 to 0·2 in for the depth of the " upper hot zone " should be regarded with reserve, in view of the thickness of the thermocouples used for measurement (⅛ in), and the fact that the surface would be disturbed by bursting bubbles, rendering its exact positioning of doubtful significance. Nevertheless, it is possible, for reasons that will be given later, that the surface temperature gradient in the liquid phase may be real.

Hot Zone. The presence of the hot zone, accumulating steadily below the surface, is clear from Fig. 4. Its temperature did not vary either with depth or with time, and the rate of conversion of cold oil into hot zone was sensibly constant. This process of conversion appears to have continued to some extent after the fire had been extinguished, although evidently at a reduced rate and accompanied by cooling of the hot zone.

In a similar experiment to that illustrated in Fig. 4 samples of oil were withdrawn from various levels in the tank during burning, and analysed, with results that are summarized in Table V.

TABLE V.

Analysis of Samples (Pool Fuel Oil).

No.	Time of sampling after ignition.	Position of sample (in below surface) and character.	Results of analysis.				
			Sp. gr.		V.R.I. (sec).		Water content (%).
			At 60° F.	At 200° F.	At 100° F.	At 200° F.	
22A	0	23 (initial oil)	0·943	—	188	45	0·3
22B	39 min	5 (cold oil, ¾ in below hot zone)	0·940	0·892	191	46	0·1
22C	40 min	21¼ (cold oil)	0·940	—	190	46	0·2
22D	1 hr 13 min	3¾ (hot zone)	0·975	0·917	1490	120	trace
22E	1 hr. 14 min	19¾ (cold oil)	0·941	—	188	45	0·1

These results show that, until conversion into the hot zone, the cold oil did not vary in character either with time or depth of origin. It was indeed the unchanged initial oil, a conclusion which is consistent with the observation that there is no temperature change whatever in the cold oil until it is converted into hot zone.

The hot zone itself (Sample 22D in Table V) is evidently the residue formed by the removal of certain lighter fractions from the original oil, and the conversion of cold oil into the hot zone appears to consist of a layer-to-layer process of "flash" distillation to the hot-zone temperature. As will be seen later, however, the fraction thus removed does not comprise the total distillate.

An A.S.T.M. distillation on the oil used showed that at the hot-zone temperature (293° C), 100 c.c. oil yielded 24 c.c. of distillate (volumes at 60° F). Data from the burning experiment allow a comparison to be made with this figure.

In the experiment to which the above analyses apply, the mean rate of conversion of cold oil to hot zone was 10·2 in/hr, and the gross rate of disappearance of oil by burning was 3·66 in/hr, all in terms of cold oil. Thus, the quantity fraction (by weight) of oil distilled was $3{\cdot}66/10{\cdot}2 = 0{\cdot}36$. From this and from the specific gravities (at 60° F) of the original oil (0·942) and of the hot-zone oil (0·975) it follows that the mean specific gravity at 60° F of the fraction removed was 0·893, assuming that it had undergone no chemical change. Thus the volume of the removed fraction per 100 volumes of original oil was $36 \times \frac{0{\cdot}943}{0{\cdot}893} = 38$, a figure higher by 14 volumes than that obtained analytically.

Two reasons for this discrepancy seem possible:—

(1) Some of the hot-zone oil was splashed into the zone of flame by the vapours rising through it from the hot–cold interface. This resulted in the complete disappearance by burning of all fractions of a proportion of the hot-zone oil;

(2) The hot zone itself was burning at its surface.

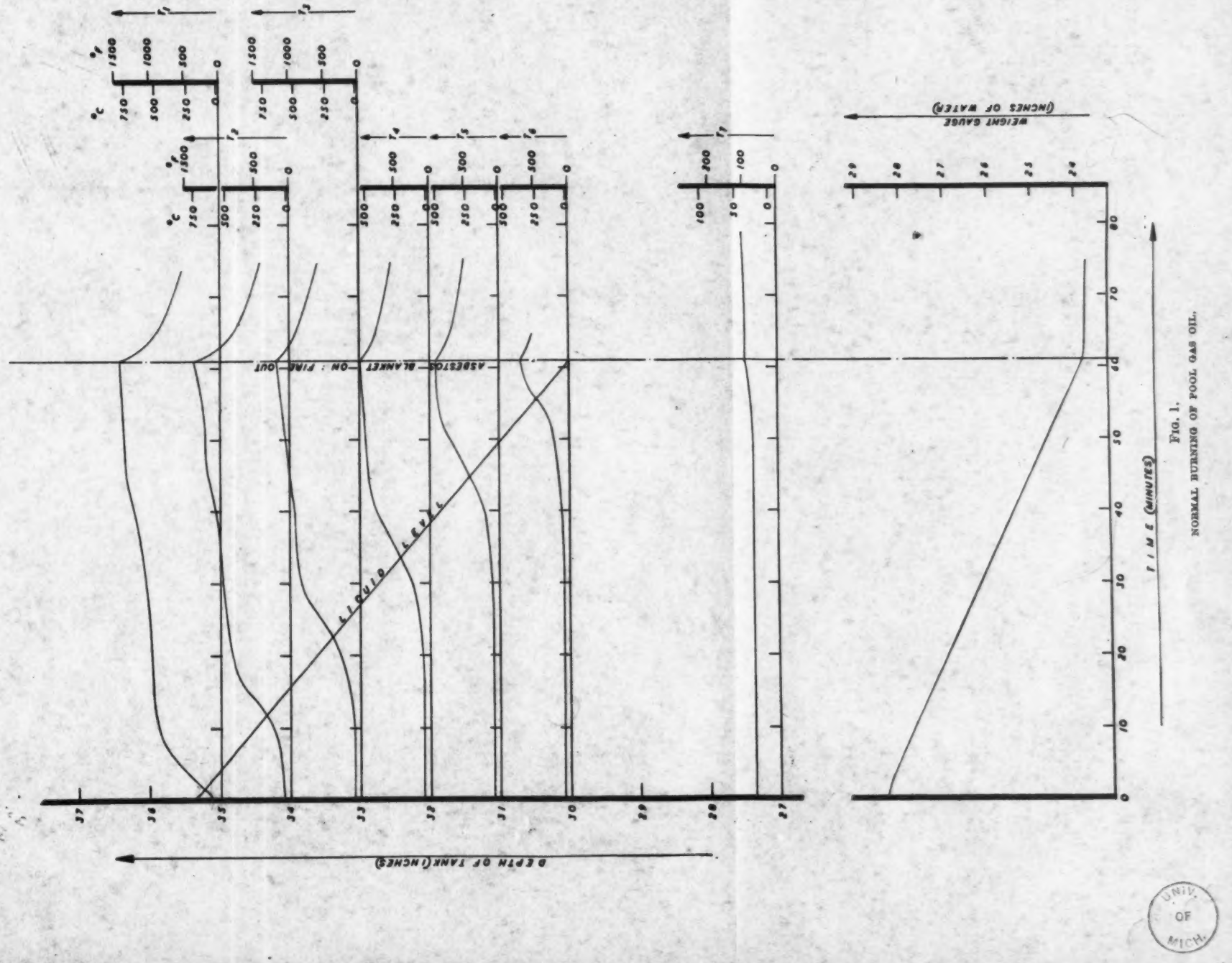
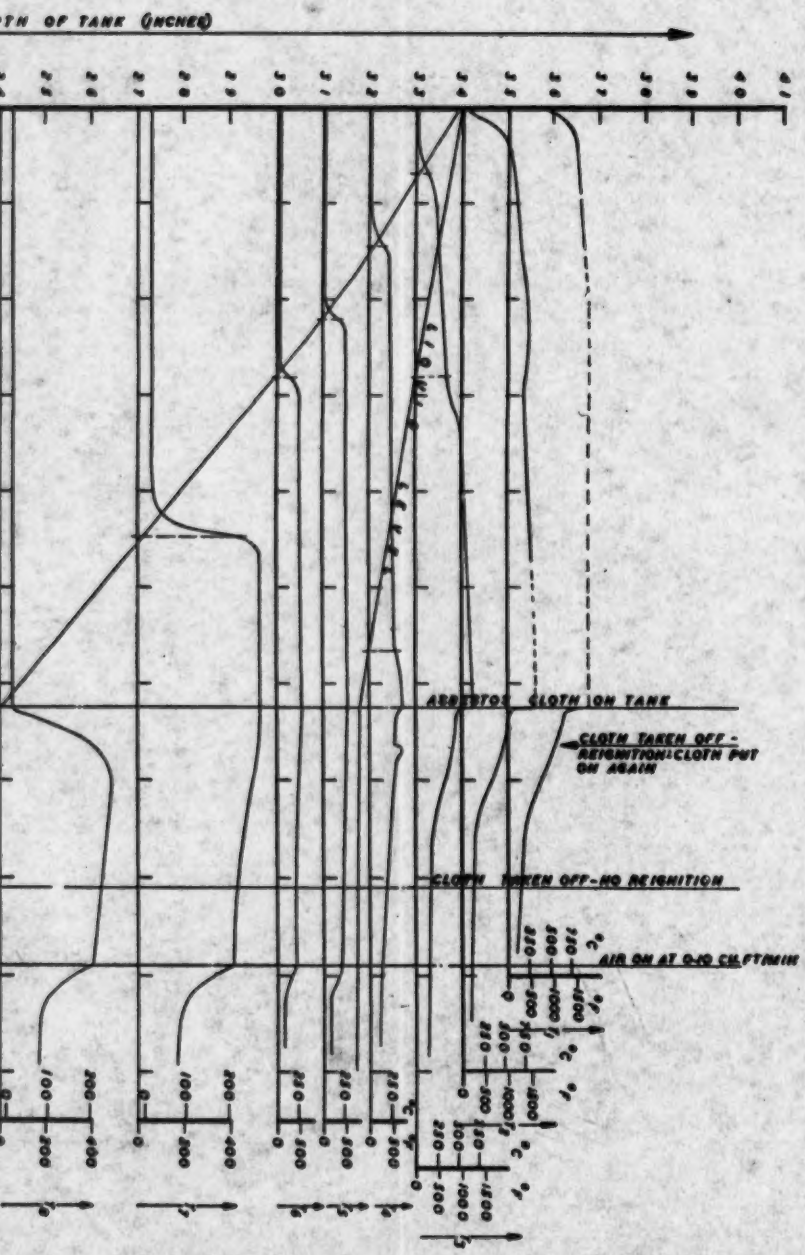


FIG. 1.
NORMAL BURNING OF POOL GAS OIL.

UNIV. OF MICH.


TH OF TANK (INCHES)
ASBESTOS CLOTH ON TANK
CLOTH TAKEN OFF - REIGNITION: CLOTH PUT ON AGAIN
CLOTH TAKEN OFF - NO REIGNITION
AIR ON AT 0·40 CU.FT/MIN

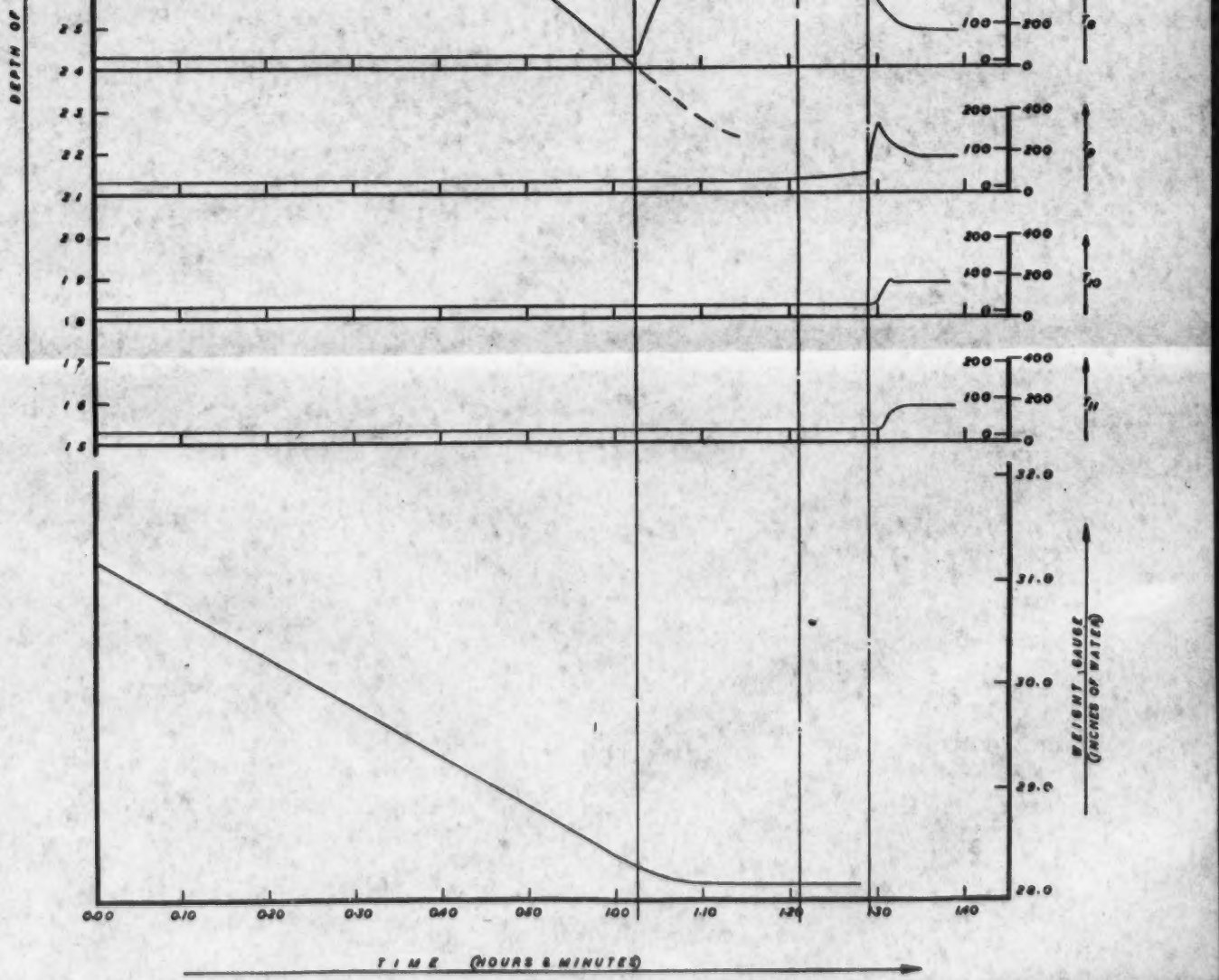
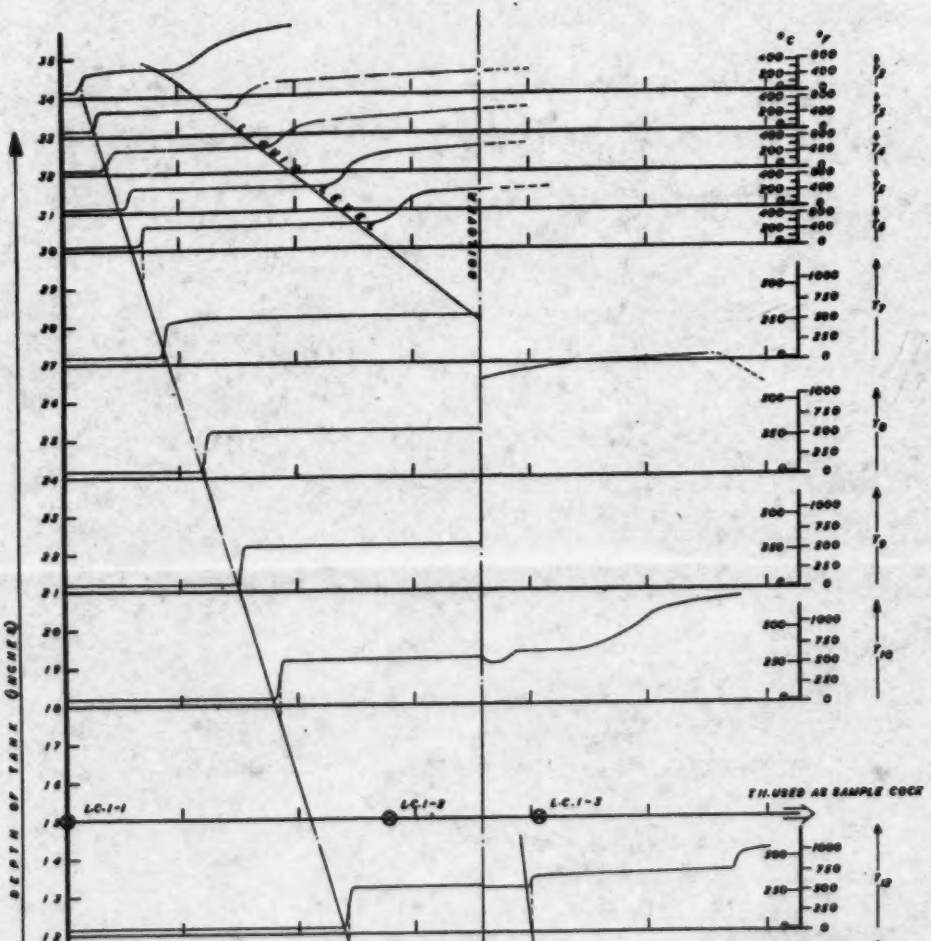


FIG. 4.

NORMAL BURNING OF POOL FUEL OIL.

UNIV. OF MICH.


°C
°F
DEPTH OF TANK (INCHES)
L.C.1-1
L.C.1-2
L.C.1-3
T.H. USED AS SAMPLE COCK

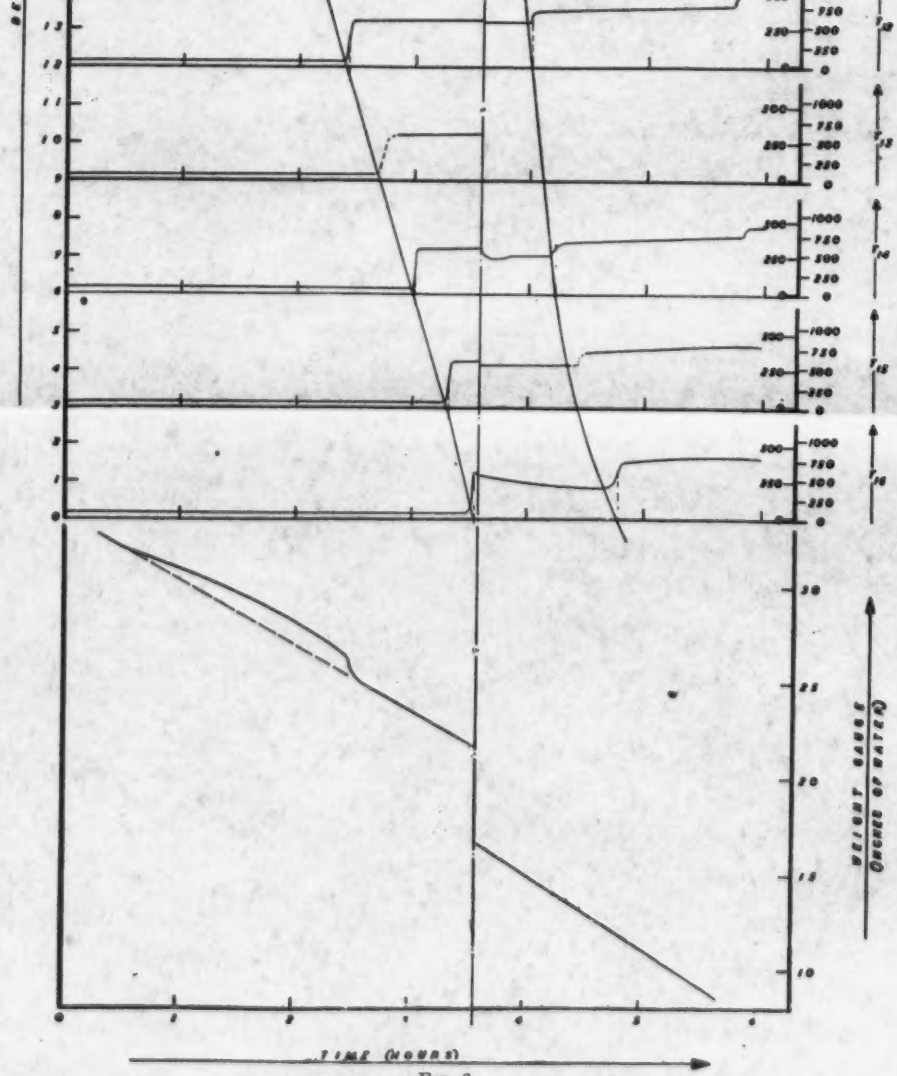


FIG. 6.

PROLONGED BURNING OF POOL FUEL OIL.

UNIV. OF MICH.

DEPTH OF TANK (INCHES)
ASBESTOS BLANKET ON TANK
L/d
3.0
2.0

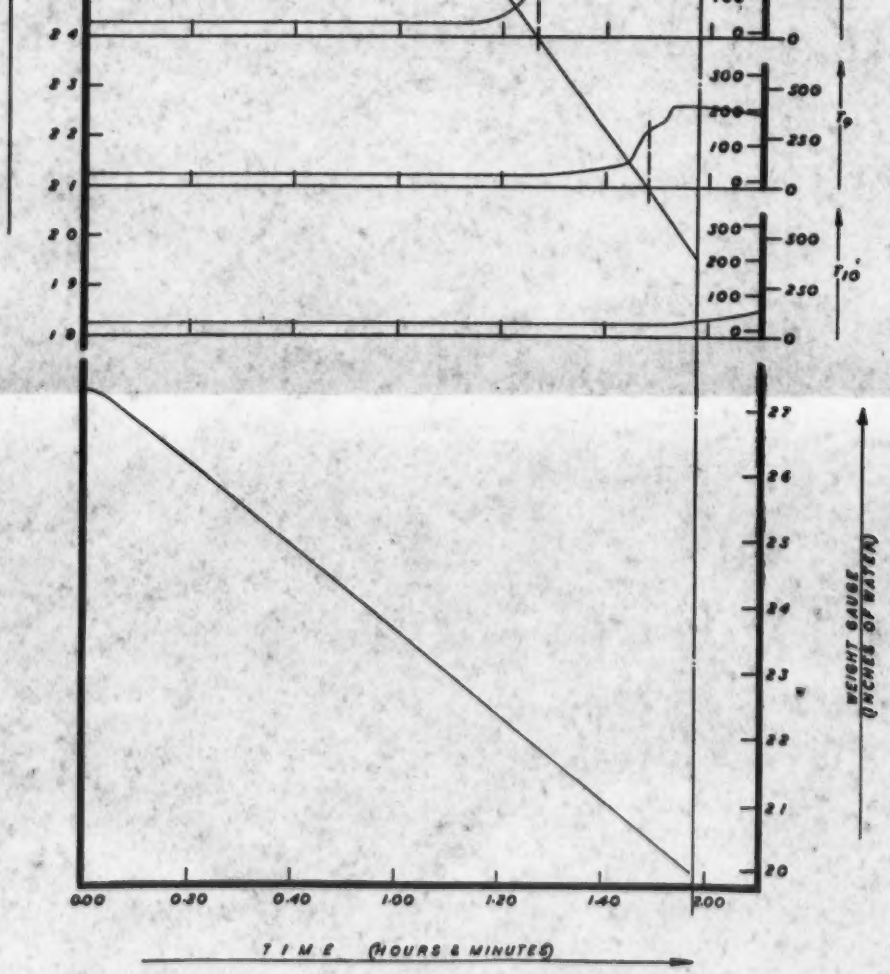
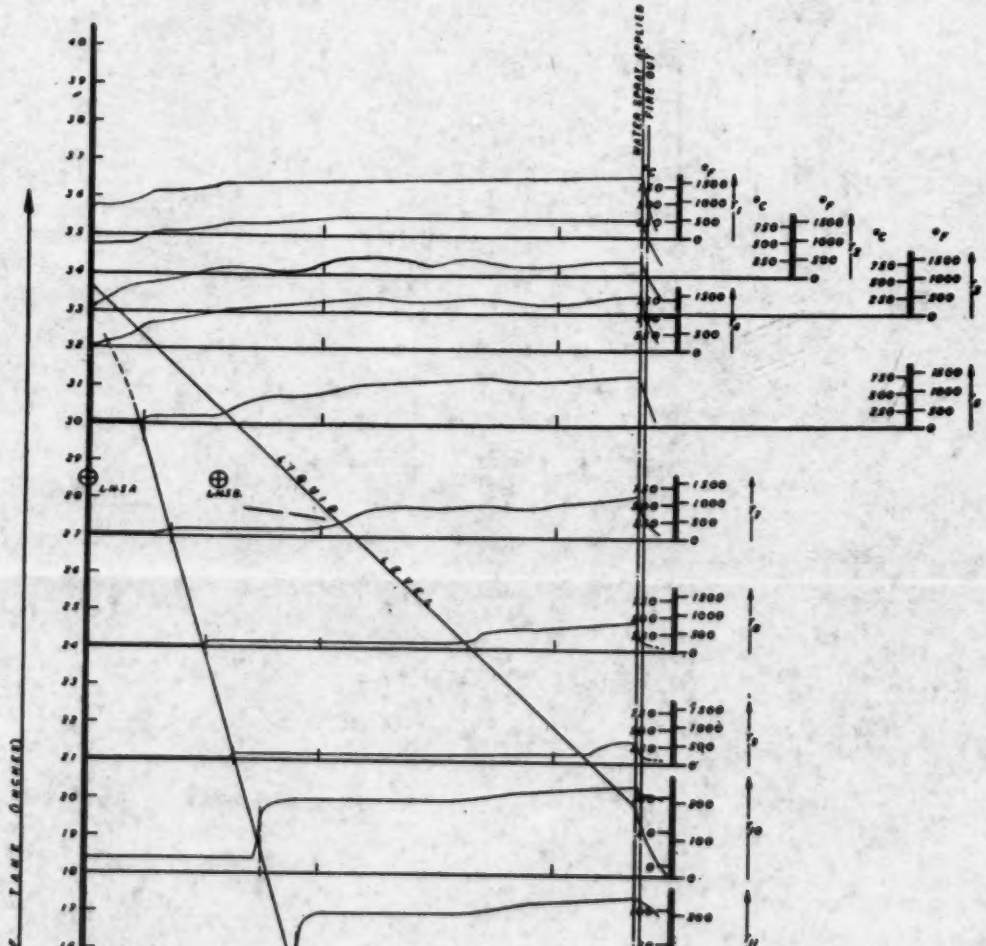


FIG. 8.

NORMAL BURNING OF SOUTH-WEST TEXAS CRUDE OIL.

UNIV. OF ILLINOIS



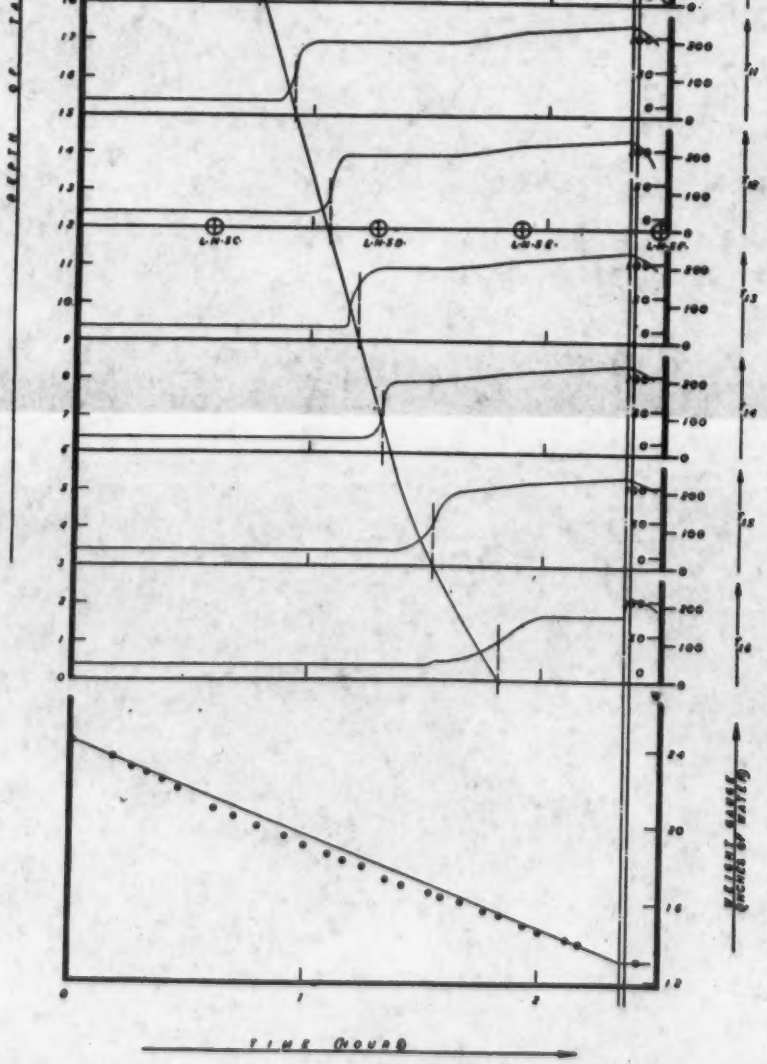
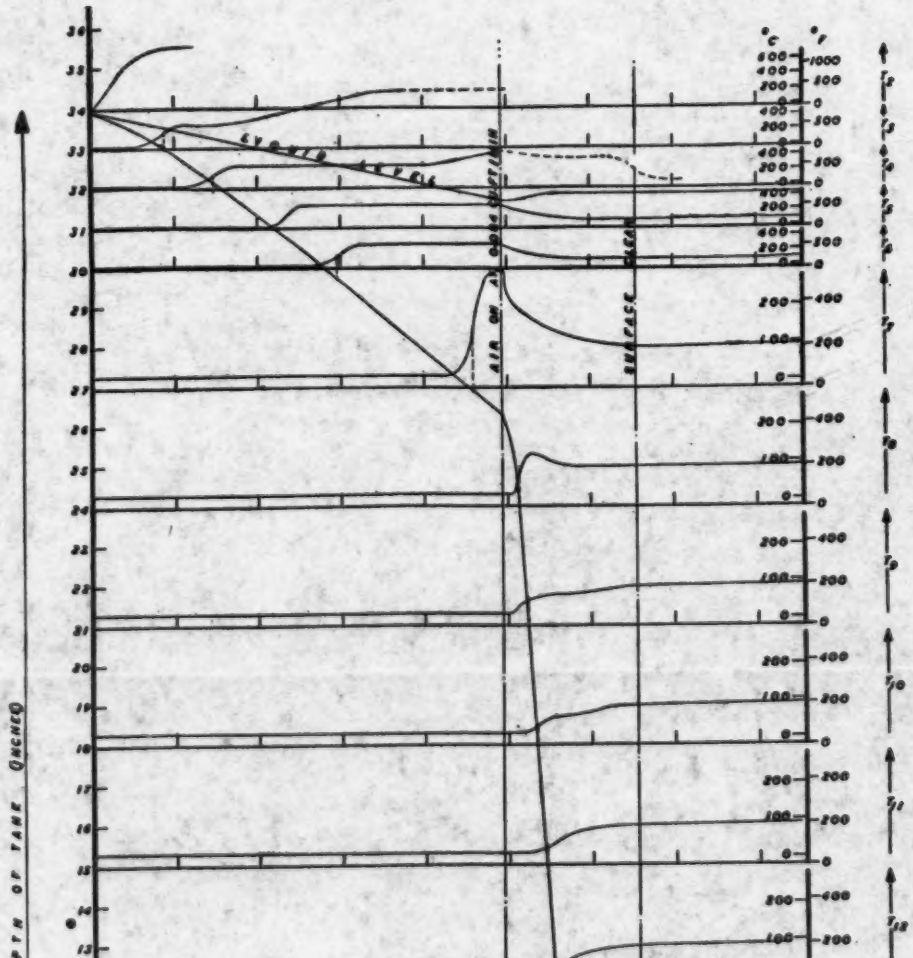


FIG. 10.

NORMAL BURNING OF POOL 72 SPIRIT (UNLEADED).

UNIV. OF MICH.


°C
°F
AIR ON
SURFACE
DEPTH OF TANK QUENCH

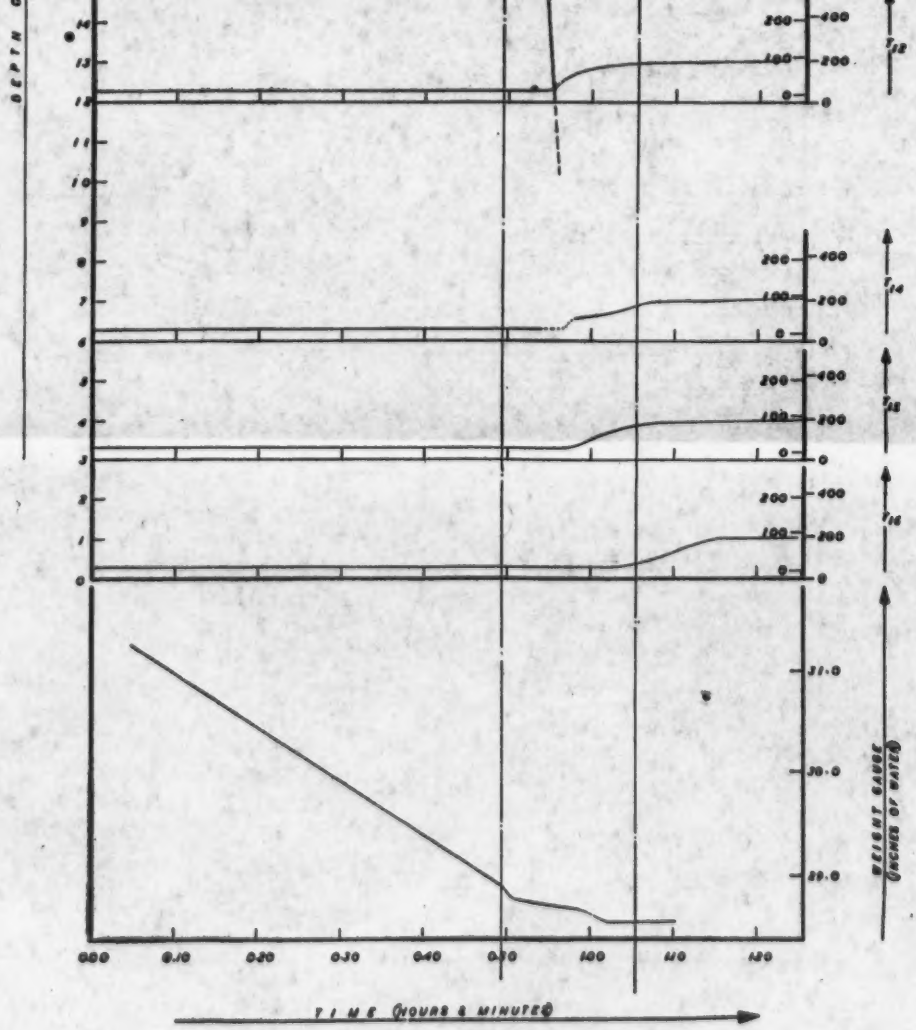


FIG. 11.

EFFECT OF AIR-STIRRING ON BURNING POOL FUEL OIL.

There is little doubt that the former was in fact responsible for some of the discrepancy, but we are in no position to say to what extent. The bursting of the bubbles in the surface of burning fuel oil can often be seen when circumstances favour visual observation. The droplets of hot oil thus discharged can be seen burning as bright specks amongst the flames.

We are unable to say at present whether the second explanation is also significant. Indications have been obtained (see Fig. 5) of a temperature gradient at the surface of the hot zone. The removal of 38 volumes of distillate per cent would imply a surface temperature of 337° C., *i.e.*, 44° C

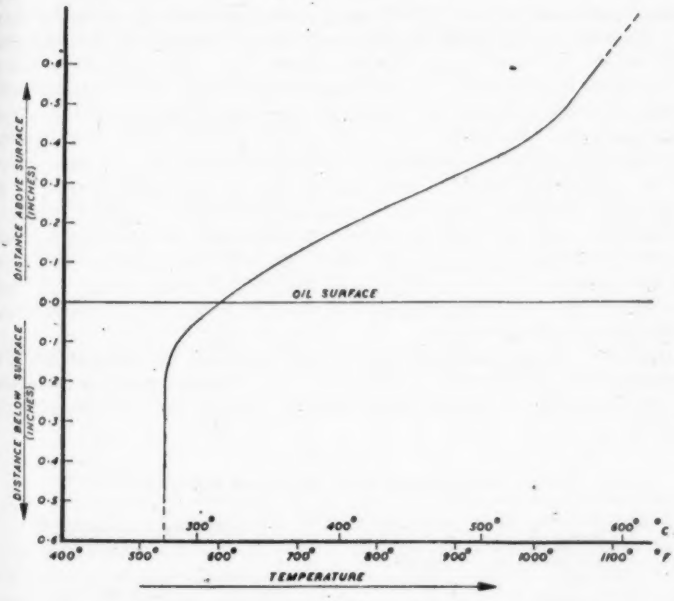


FIG. 5.

POOL FUEL OIL—TEMPERATURE DISTRIBUTION NEAR SURFACE AFTER BURNING 45 MIN.

above the hot-zone temperature. Experience with the distillate oils suggests that this difference might occur over a band that would be too narrow to be precisely observed by our methods, especially when the stirring effect of the vapours rising from the hot–cold boundary is taken into account. In this connexion, as well as in the matter of splashing referred to above, it is significant that the volume rate of discharge of vapours through the hot-zone would be about 2 cu ft/min. It will be appreciated when Part II of this paper has been considered that this implies vigorous agitation of the liquid.

Prolonged Burning. In Fig. 6 are shown the results of an experiment in which burning was prolonged beyond the time at which the whole contents of the tank had become converted into the hot zone. Two points of major

interest are revealed—the occurrence of boilover, and the repetition of the cycle of hot-zone formation.

The occurrence of boilover coincided, as nearly as can be judged, with the arrival of the hot zone at the tank bottom, and resulted in a fall in temperature of the oil. Such an occurrence has, in the past, been associated with the presence of water on the tank bottom, and it is perfectly reasonable to suppose that in such circumstances an eruption would occur. In the present experiment, however, the tank was free from moisture before the oil was admitted. The oil itself had a water content of 0·3 per cent.

Although it is not possible to allow for scale effects, the eruption did not appear to correspond in violence to happenings on the large scale that have been described. Nevertheless this experiment, supported by others of which we do not need to give details, shows that boilover is to be feared even with oils that have only a small water content and in dry bottom tanks. By way of justification it must be remembered that when the whole contents of the tank are "hot zone" they are at their I.B.P. They are therefore in equilibrium with the conditions of their formation, but the equilibrium will be violently disturbed if their vapour pressure is suddenly reduced by the presence of steam—even that derived from a small amount of water.

Although some of the thermocouples were put out of action by the boilover, the record is sufficient to indicate that the process of hot-zone formation was subsequently repeated at a higher level of temperature. Indeed, there is evidence on thermocouples T12 and T14 that a third cycle followed the completion of the second.

Samples of oil were taken at the positions and times indicated in Fig. 6 to demonstrate the constitution of the first and second hot zones as compared with the initial oil. The results of analysis of these samples are given in Table VI.

TABLE VI.

Analysis of Samples (Pool Fuel Oil).

No.	Time of sampling after ignition.	Character of sample.	Results of analysis.		
			Sp. gr. at 60° F.	V.R.I. at 100° F. (sec).	Water content (%).
1A	0	Initial oil	0·943	187	0·3
1B	2 hr 46 min	First hot zone	0·9795	2,430	trace
1C	4 hr 6 min	Second hot zone	0·996	17,300	trace

The hot-zone temperatures in this experiment were—first 296° C (mean: there was a rise in the later stages of a few degrees); second, 382° C rising slowly to above 400° C; third (?), over 540° C. In succeeding cycles the fraction of the oil removed fell off, for while the gross rate of loss of oil only increased slightly, the rate of conversion of "cold" oil increased greatly, as can be seen from Fig. 6. Although data do not warrant a precise statement of fractions removed of the remainder after the first (which was 37 per cent), the second appears to have been about 17 per cent, *i.e.*, about 11 per cent of the original oil, and the third (*sic*) very roughly 7 per cent, *i.e.*, 3·5 per cent of the original oil.

Effects of External Conditions on Characteristics. In a fairly extensive group of experiments on Pool fuel oil, common stock was employed. Analyses on samples taken from the initial oil in individual runs gave the following results.

Specific gravity at 60° F.	0·942 ± 0·001
Viscosity, Redwood I at 100° F	190 ± 10 sec.
Water content	0·25 ± 0·05%.

As the burning experiments were carried out in the open under somewhat varied weather conditions, quantitative burning characteristics showed some variations. In Table VII these measured characteristics are set out together with an indication of weather conditions, for those experiments which were of sufficient duration to give definite readings.

TABLE VII.

Variation in Burning Characteristics of Pool Fuel Oil.

No. of expt.	Duration of measurements.	Gross rate of loss of oil (in/hr).	Rate of conversion of cold oil to hot zone (in/hr).	Fraction removed (% by weight).	Hot zone temperature (° C).	Wind (estimated Beaufort scale).	Rain.
11	40 min	3·84	10·0	38	288	2–4	Squally
1	3 hr 15 min	3·71	10·0	37	296 †	2–3	None
22	1 hr 15 min	3·66	10·2 *	36	293	0–1	None
10	1 hr 15 min	3·62	9·5	38	288	3–5	None
16	45 min	3·52	9·7 *	36	288	1	Slight, occasional
9	2 hr	3·38	9·0	38	288	3–5	None
15	45 min	3·24	9·0	36	277	2–4	None

* Not well-defined. † Mean value; slight progressive rise.

It is seen that although the rate at which oil is affected by the fire is somewhat variable under different conditions, the hot-zone temperature and the fraction of affected oil consumed are much less so. In spite of this, occasional anomalies were observed. Thus, in one experiment where conditions appeared to be similar to those included in Table VII, rates of loss of oil and assimilation of 2·7 and 9·5 in/hr respectively were observed. This corresponds to a fraction removed of 28·5 per cent by weight, but the hot-zone temperature was 288° C as usual.

Effect of Scale. A burning experiment was carried out in the large tank (9 ft dia) using oil having similar properties to those of the oil already considered. The gross rate of loss of oil was 4·90 in/hr of cold oil and the rate of assimilation into the hot zone was 14·0 in/hr, rising after about 1 hr 20 min to 17·8 in/hr. Thus the fraction removed changed from 35 to 28 per cent. These figures compare with 36 to 38 per cent on the small scale for a similar oil, although the actual rates differed considerably in the two cases. The hot-zone temperature was about 243° C throughout.

Table VIII shows the results of analyses on samples taken in the course of this experiment. It is seen that the hot-zone oil was similar in character to that obtained on the smaller scale.

TABLE VIII.

Analysis of Samples (Pool Fuel Oil).

No.	Time of sampling after ignition.	Level of sampling (initial oil level 14 ft 1½ in).	Character of sample.	Results of analysis.		
				Sp. gr. at 60° F.	V.R.I. at 100° F (sec).	Water content (%).
19	0	12 ft 3 in	Initial oil	0·944	192	0·7
20	1 hr 6 min	13 ft 0 in	Hot zone	0·973	1425	0·1
21	1 hr 6–11 min	12 ft 3 in	Cold oil	0·942	192	1·1
22	1 hr 32 min	13 ft 0 in	Hot zone	0·977	1240	trace
23	1 hr 34 min	12 ft 3 in	Hot zone	0·970	1270	trace

Wet Oils. In other experiments on the large scale in which a fuel oil with a high water content was employed, thermometric evidence of frothing was noted in two cases and in a third a slopover took place apparently quite spontaneously and without external warning. The rate of development of froth was much the same in each case, reaching 1·5 to 2 in in 10 min, 4 to 5 in in 20 min, and 8 in in 30 min. In the third experiment which was prolonged beyond this point the froth filled the available ullage (32 in) at 41½ min and a slopover occurred. It appears that the oil in these experiments was not uniform, and samples having water contents from 3 to 11·3 per cent were obtained. A quantity withdrawn for a small-scale test had a water content of 12·3 per cent. In this latter test, difficulty was experienced in lighting the oil, which repeatedly frothed and extinguished the fire. When burning was ultimately established a series of slopovers took place (six in about two hours) which precluded any very satisfactory record of burning behaviour, but clearly demonstrated the hazard attending the burning of oil of this character.

(2) *Crude Oils.*

Crude oils from three sources were examined—British (Eakring), Iranian, and South-west Texas. Qualitatively, they behaved in similar manners to one another and to fuel oil. Quantitatively, they were individualistic and were distinguished from fuel oil by a marked inconsistency of behaviour both in a single experiment and on different occasions. For the sake of brevity it will be expedient to take the established behaviour of fuel oil as background and note principally those points of similarity or difference which the crude oils displayed.

Prolonged Burning. Fig. 7 illustrates the results obtained in a preliminary experiment in which Iranian crude oil (sp. gr. at 60° F = 0·861) was burned for several hours. It will be seen that the conversion of oil into hot zone proceeded to completion and that a boilover then occurred (in spite of the fact that neither the oil nor the tank contained a measurable amount of water). Up to this point the hot-zone temperature had been rising continually (*cf.*, fuel oil in Fig. 6 for a much more gradual rise). The boilover led to a drop in temperature however, followed by evidence of the second cycle of hot-zone formation.

First Cycle of Hot-zone Formation. The remaining experiments on burning behaviour of the crude oils were confined to an examination of the first

cycle of hot-zone formation. An example is illustrated in Fig. 8 which refers to S.W. Texas Crudes (sp. gr. at 60° F = 0·828). In this experiment the fire was extinguished by means of a blanket and the locus of the oil surface determined in the manner already explained. In Fig. 9 the distribution of the temperature in the neighbourhood of the surface after 45 min burning is shown.

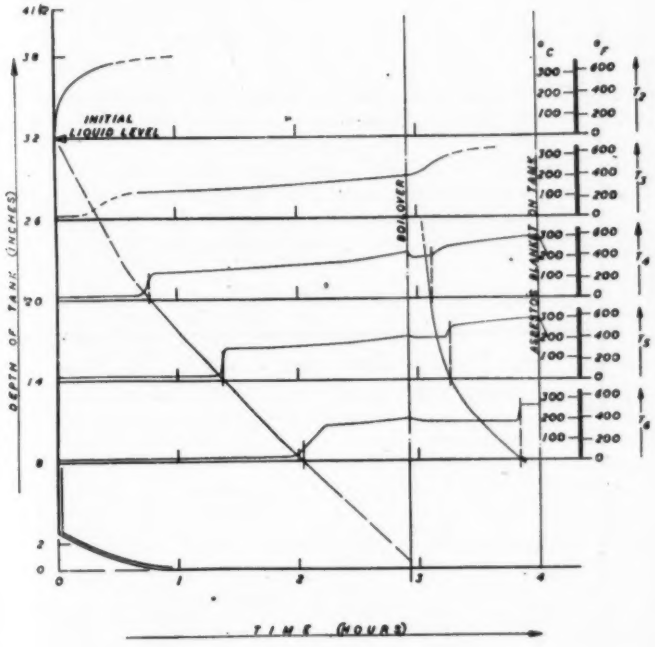


FIG. 7.

PROLONGED BURNING OF IRANIAN CRUDE OIL.

A noteworthy observation regarding the Texas crudes, which is illustrated in Fig. 8, was the slow development of the hot zone. This implies the removal of a large fraction by distillation and burning. The other crudes were more comparable with fuel oil in this respect. As shown in Fig. 8 samples were taken after about 1 hr 20 min burning. At this time the rate of conversion of oil into hot zone (which, like the hot-zone temperature, showed a gradual increase throughout the experiment) was 7·5 in/hr and the gross rate of loss of oil (which was steady) was 4·94 in/hr. Thus the fraction removed was 0·66. The specific gravity (at 60° F) of the initial oil and hot-zone oil being 0·828 and 0·879 respectively, the mean specific gravity of the fraction lost was 0·805. Thus the volume fraction removed was 68 per cent. This compares with an analytical figure of 46 per cent at the hot-zone temperature of 232° C. Those remarks relating to the similar

discrepancy with fuel oil may be applied qualitatively in the present instance. The distillation of 68 per cent (volume) would imply in this case a temperature of 277° C.

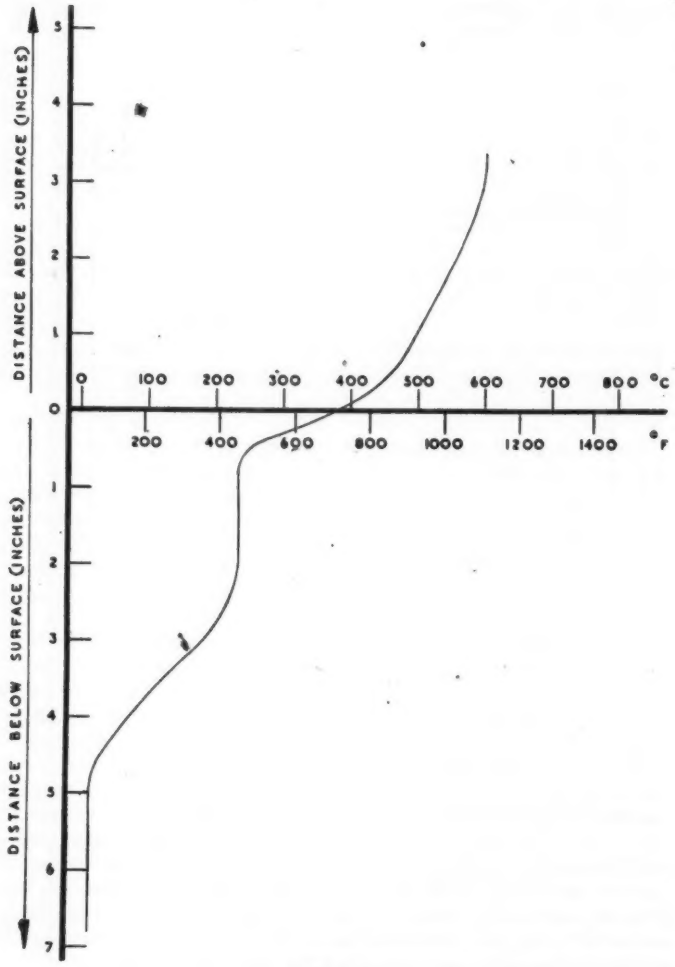

DISTANCE ABOVE SURFACE (INCHES)
DISTANCE BELOW SURFACE (INCHES)
0 100 200 300 400 500 600 700 800 °C
200 400 600 800 1000 1200 1400 °F

FIG. 9.

SOUTH-WEST TEXAS CRUDE OIL—TEMPERATURE NEAR SURFACE AFTER BURNING 45 MIN.

As has been indicated there was some variation in burning properties revealed in the experiments carried out on crudes, but the following were the

means of all the values obtained for the fractions (by weight) removed during the first cycle of burning.

British crudes	25 per cent.
Iranian crudes	28 per cent.
S.W. Texas crudes	61 per cent.

The last-named came nearest, amongst hot-zone forming oils, to the non-hot-zone-forming type, in which the fraction removed is to all intents and purposes 100 per cent.

(3) *Pool Motor Spirit.*

Under this heading both leaded and unleaded samples of Pool 72 spirit were examined. The results of a prolonged burning test on the latter (sp. gr. at 60° F = 0·7415) are shown in Fig. 10. It will be seen at once that a hot zone was formed in spite of the fact that the spirit was a distillate. The complete conversion of the cold spirit into hot zone was not, however, followed in this case by the formation of a second hot zone. Instead, the whole of the oil heated up continuously and uniformly at a rate of about 0·5° C/min.

Samples taken throughout the experiment, as indicated in Fig. 10 gave analyses as shown in Table IX.

TABLE IX.

Analysis of Samples (Pool Motor Spirit, Unleaded).

No.	Time of sampling after ignition.	Character of sample.	Results of analysis.				
			Sp. gr.		Distillation.		
			At 60° F.	At 100° F.	I.B.P.	50%.	F.B.P.
5A	0	Initial material	0·7415	0·7235	53° C	121° C	200° C
5B	33 min	Hot zone	0·761	0·744	64	137	203
5C	34 min	Cold spirit	0·7424	0·7248	42	119	199
5D	1 hr 17 min	Hot zone	0·7593	0·7423	58	134	202
5E	1 hr 54 min	Hot zone during heating	0·765	0·748	68	140	204
5F	2 hr 29 min	Hot zone after extinction	0·771	0·754	86	143	207

These results make it clear that the mechanism of formation of the hot zone is the same as that with fuel oil, but after complete conversion of the tank contents into hot zone the observed heating-up corresponds with the progressive removal of fractions from the whole bulk at once. It would appear that this is due to the formation at the liquid surface of a residue, the specific gravity of which (at the temperature of formation) is not so much less than that of the underlying liquid that it is able to form a discrete hot zone.

The steady temperature of the hot zone in this experiment was 90° C. According to an A.S.T.M. distillation on the material used, a fraction of 19 per cent (by volume) was distilled off at this temperature. Under fire

conditions the fraction removed was a little variable, being 40½, 35, and 34 per cent (by volume) taken over successive periods of 30 min from the commencement of the fire. Even neglecting the first value, which might be anomalous since it refers to the initial stages, it is seen that, as in the case of fuel oil, the fraction removed is greater than indicated analytically.

During the first 30 min of uniform heating of the oil in the second stage, 14·4 per cent of the tank contents were consumed. The uniform temperature at the end of this period was 102° C, at which temperature it was found that about 15 per cent of a sample of the normal hot zone would distil under laboratory conditions. This result, supported by others which also cover leaded spirit, confirm the view already expressed regarding the mechanism of the second-stage heating-up process.

From the measured specific gravities of the hot zone and the cold spirit at 60° F, and the fraction removed by burning, the mean specific gravity (at the same temperature) of the fraction thus removed can be calculated. In the experiment illustrated in Fig. 10 it comes to 0·698. By a similar calculation it can be shown that the value for the fraction removed after 40 min in the second stage (uniform heating) is 0·665. This difference is consistent with the view that in the first stage of the experiment a proportion of the hot zone itself was being consumed in addition to distillate from the hot–cold interface.

In an experiment with leaded spirit in which the analytical results did not suggest the removal of so large a proportion of hot zone, the calculated specific gravities of the burned fractions (at 60° F) were closer, viz., 0·706 in the first stage and 0·700 after 38 min in the second stage. In both experiments therefore specific gravity measurements supported the inference drawn from distillation data.

Quantitative burning characteristics were found to be rather more variable with motor spirit than with fuel oil, and even in the same run inconsistencies of behaviour were recorded, of which a moderate example is seen in Fig. 10. In one extreme instance (unleaded spirit) the accumulation of the hot zone slowed down at an intermediate stage and finally ceased. The spirit was then behaving substantially as a non-hot-zone-forming oil except that it had an appreciable though constant hot zone, the temperature of which was slowly rising. The phenomenon has not so far been reproduced. This type of instability of the hot zone, which was also manifest in a more mild form in other experiments by the poor definition of its lower boundary by comparison with fuel oil, is attributed to the low viscosity and to the small specific gravity difference between the hot and cold zones.

In another experiment on (leaded) spirit, an eruption occurred during the uniform heating-up period, about 32 min after the complete conversion of the tank contents into hot zone. At this moment the uniform temperature was 88° C. This fact, together with the complete absence of water (so far as is known) from the tank and its contents, seems to dissociate the phenomenon altogether from water, and to suggest that it arose as a result of the instability of the liquid, possibly due to superheating during the period of uniform temperature rise. The fact that the eruption occurred almost immediately on commencing to withdraw a sample from the tank lends support to this view.

Discussion.

Theory of hot-zone formation. Our view of the mechanism of hot-zone formation does not differ from that expressed by Hall, except in one particular. He claimed that the specific gravity of distillation residues at their temperature of formation showed a minimum in the case of certain oils. Thus, heavy ends formed at the surface were supposed in these cases to have a greater density than the hot-zone oil and thus to fall through it. We find no support for this interpretation but consider that any heavy ends formed at the surface will actually have a lower specific gravity than the hot zone. There will, nevertheless, be a tendency for mixing to occur due to the stirring effect of the vapours released from the interface at the bottom of the hot zone. The way in which this mixing takes place will be clearer when the second part of this paper has been considered.

The composition of the hot zone appears to us to be determined by purely thermal considerations. Heat is transmitted from the flames to the hot zone, where a small proportion is possibly employed (near the surface) in evaporation and the rest is conveyed through the hot zone by circulation of the oil. This part is transmitted to the cold oil across the hot–cold oil boundary and is employed in heating and evaporation. The temperature and composition of the hot zone are thus determined by heat transmission coefficients at the surface of the oil and at the hot–cold oil boundary, together with thermal properties of the oil. This balance being established the rate of conversion of cold oil into hot zone and the gross rate of consumption of oil are both fixed.

We have not completed a mathematical treatment of this process, but are endeavouring to do so. If this can be done it may be possible to predict the burning behaviour of an oil from its distillation curve and other physical properties.

Practical Implications in Firefighting. In the course of the foregoing account, reference has been made at several points to the hazards of boilover, slopover, and allied phenomena. These may be associated almost exclusively with those oils in which a proportion of the heat of combustion is continuously retained in the oil itself, thus creating a substantial reservoir of heat which may at any time divert to the sudden boiling of the oil itself, or of water with which it comes into contact.

It should be noted that although this characteristic generally implies a hot-zone-forming oil, it is not necessarily so. The heat content of certain distillates (such as lubricating oils) having a high surface temperature may be sufficient to cause a degree of frothing in contact with water or foam that might be hazardous with small ullages. It is an undoubted advantage of such oils, however, that their heat content does not increase notably during burning when once the initial stages have been passed.

It is, then, the hot-zone-forming oils that principally command attention, and especially those in which the hot-zone temperature exceeds the boiling point of water, for at present no extinguishing technique is available on the large scale that does not involve the application of water either as such or in the form of foam. We have demonstrated on more than one occasion that to apply foam in such circumstances is distinctly hazardous. Thus, for example, when air foam was applied by overhead pourer to Pool fuel oil

which had burned for only ½ hr (depth of hot zone 8 in) in the large tank and had 2 ft 6 in ullage, a dangerous slopover occurred. A repetition of the experiment with the application of chemical foam yielded a similar result. In both cases arrangements had been made to continue foam application in spite of the slopovers, and the tank fires were finally quelled in this way, although auxiliary measures were of course needed to deal with the surrounding fires. An investigation into the effects of applying foam at different rates to burning fuel oil containing different hot-zone depths has now been undertaken and it is hoped to report on the results in due course.

We are brought, however, to the conclusion that there is considerable hazard in dealing with a tank fire in either crudes or fuel oils. It is true that the probability of fuel-oil-tank fires in times of peace is not great, but such are known to occur, and fuel oil may obviously become involved in a fire originating in more ignitible materials. Crudes present a live hazard at any time, however, since the flash-point is often below and is in any event not much above ordinary temperatures. The investigations described in the second part of this paper suggest what appears to be the logical way out of this dilemma.

The hazards of gasoline fires are revealed as partially of a different character. The highest normal hot-zone temperature recorded in our experiments was 91° C. In such circumstances the ordinary hazards of slopover on the addition of foam or water, or boilover with a wet tank bottom, would not be present. It is by no means certain, however, that normal hot-zone temperatures of more than 100° C would not be attained with certain blends, in which case these hazards would exist.

The margin of safety is in any event narrow and the uniform heating which follows complete conversion rapidly brings the bulk temperature above 100° C. At this stage, as we have found by experience, the application of water leads to slopover. Furthermore, with a wet tank bottom a mild boilover might occur and finally there is the possibility that we have observed of spontaneous eruption of the gasoline itself.

It may be considered that this late stage in the burning of gasoline, wherein lie most of the hazards, will rarely be reached in practice. It must be remembered, however, that the rate of conversion into hot zone can be much greater with gasoline than with the heavy oils : we have observed rates between 24 and 36 in/hr, and these would probably be increased on the large scale. Thus in a few hours the whole contents of large tanks could be converted into hot-zone spirit.

Part II.—Effects of Disturbing the Normal Burning of Petroleum Products by Agitation.

Introductory.

In the first part of this paper the thermal aspect of the burning in bulk of representative petroleum products has to some extent been elucidated. A picture has been presented of a balanced process upon which maintenance of the fire appears to depend. In the light of this conclusion it is not unnatural to enquire as to the effects of disturbing this thermal process and whether, by throwing it out of balance at some point, fire might not be controlled without undue expenditure of energy.

It is clear from the results that have been given that, in the earlier stages at least, there exists in all oils burning in bulk, a considerable reservoir of cold liquid. This reservoir is consumed in time in some cases (the hot-zone-forming oils), but in others (non-hot-zone-forming) it does not entirely disappear until almost the whole of the oil has been burnt. In all but the most volatile petroleum products this reservoir oil is not able to burn until its temperature has been raised by a comparatively slow process of transfer of heat emanating originally from the flames. What would be the effect of causing the cold reservoir to mix with those zones across which the transmission of heat is taking place?

In order to answer this question in some of its aspects, experiments have been carried out in which an endeavour was made to project the cold-oil reserve into the hot zone (if any) or into the surface layers of the burning liquid. Three methods of experiment have been employed :—

(1) Air was bubbled up through the oil from an inlet at or near the bottom. As a variant of this, the effects of lumps of solid carbon dioxide thrown into the tank have also been examined;

(2) Oil taken from the side of the tank was re-injected vertically through a nozzle in the bottom at such a velocity as to disturb the surface;

(3) Oil taken from the bottom of the tank was pumped directly into the hot zone (if any) through a side inlet at a suitable level, or through a floating distributor.

The first of these methods (air-stirring) has been applied in small-scale tests to all the grades of oil examined, and to Pool fuel oil in large-scale tests. The second (oil-jet stirring) has been examined to a limited extent in large-scale tests with fuel oil. The third was used in preliminary experiments on the small scale. The three methods, of course, have certain principles in common, and we shall adopt the plan of discussing air-stirring fairly fully and making brief reference to the other two techniques. The methods of observing effects of these stirring processes on temperatures, burning rates, and other characteristics were the same as have been outlined previously.

Air Stirring.

Effects on non-hot-zone-forming Oils.

A preliminary series of experiments was carried out in which the effects of air-stirring on all the oils of this class listed in Table II, excepting marine diesel, were observed. The preliminary time of burning was in general about 1 hr, after which air was injected at a rate of 0·1 cu.ft/min through a 1-in inlet in the centre of the tank bottom. The results were similar in all experiments excepting only those with the two most volatile members (benzol and white spirit) and the two most viscous (lubricating oils 17 and 20). In the course of a few minutes, flames cleared from the oil surface leaving a ring of oil burning in contact with the hot tank walls. In most cases this residual fire sooner or later went out. It consisted of two elements —the burning of a narrow annulus of oil surface in contact with the hot walls and wick-burning on soot, formed on the walls above the liquid surface. It could be extinguished quite readily by cooling the tank

walls. In the case of benzol, the measured rate of loss of oil by burning was reduced by 80 per cent, and in white spirit the reduction was 92 per cent. With lubricating oil 17, the fire was extinguished, but only after more than an hour of stirring. With lubricating oil 20, the fire could not readily be extinguished until the air flow rate was increased to about 2 cu.ft/min.

Records of oil temperature taken during stirring showed that the effect was to raise cold oil into the hot region near the surface, thereby cooling it. Ultimately, the cold oil entrained by air bubbles, having washed away the hot layer, reached the surface itself, and, by cooling and displacing the hot oil there, interrupted the burning process. It is clear that at this stage success in stopping the fire depends on cold oil being fed to and across the surface at such a rate that heat transmission from the flames is insufficient to maintain the supply of vapour. With a sufficiently volatile oil the bulk temperature of the oil after mixing (only a little above the original temperature if mixing is rapid) may be in itself high enough to maintain burning. In this case stirring cannot be fully effective. The experiments with white spirit, which was stirred rather slowly at first, and vaporizing oil are of interest as defining this limiting condition rather closely. Relevant observations are shown in Table X.

TABLE X.

Observations on Limitations of Air Stirring.

Grade.	Burning rate reduction on stirring, %.	Lowest mixed oil temperature, ° C.	Flash point (Abel), ° C.	Distillation range, ° C.	
				I.B.P.	F.B.P.
Pool white spirit . .	92	70	39	164	189
Pool vaporizing oil . .	100	39	34	165	250

It was clear from the temperature records for the experiments with the heavy lubricating oils that the ineffectiveness of air stirring in these cases was due to inefficient mixing of oil by the air on account of high viscosity. With grade 17 (719 cs at 100° F) mixing proceeded only very slowly at first, but when as a result of this slow mixing the bulk temperature had been raised slightly, thus reducing the viscosity, mixing became increasingly rapid. With grade 20 (1389 cs at 100° F) this preliminary mixing was still slower and was eventually achieved by the use of very high air rates.

From these preliminary results it is clear that a standard and reasonable rate of air stirring can extinguish fires in all the non-hot-zone-forming oils with approximately the same facility, unless the flash point is below about 30 to 40° C, or the viscosity is unusually high.

In cases where air was applied at an insufficient rate to effect extinction, or where the grade was too volatile to be completely controlled, continuation of burning and stirring together led to a steady and uniform heating up of the bulk of the oil at a rate which decreased with increasing stirring rates. It is not difficult to see that this was due to the passage of cold oil across the surface at such a rate that sufficient heat could be transmitted from the flames to maintain the fire (though possibly in a less intense form). The

heated residue displaced by cold oil would then mix with the bulk, raising the general temperature.

The point is of practical importance, since in normal burning the heat content of an oil of this type does not increase after the initial stages. It is clear, however, that unsuccessful stirring will convert the whole oil into a heat reservoir, which if the temperature rises to 100° C, or perhaps to the I.B.P. of the oil, will render it liable to the hazards that have up to the present been attributed only to hot-zone-forming oils.

Effects on hot-zone-forming Oils.

(1) *Fuel Oil.* The first effect of air stirring on a burning oil in which there is an appreciable depth of hot zone is to lower the temperature of the latter by admixture of the cold oil below, with the necessary consequence that the hot zone (now cooling) extends further and further down the tank until mixing is complete. In some experiments the extension of the hot zone in this way was clearly visible on the temperature records, but in others the line of division from the cold oil below became increasingly diffuse and gave place to a temperature gradient over most of the oil depth which flattened out until uniformity was reached. The results of a typical air-stirring experiment with Pool fuel oil are shown in Fig. 11.

With the bulk of the oil at uniform temperature the fire usually *appeared* unabated, except in special circumstances that will be referred to later, but the burning rate was generally somewhat reduced (see Fig. 11). At this stage circumstances were evidently much like those prevailing at the commencement of stirring of a non-hot-zone-forming oil. The bulk oil temperature was higher, however, by an amount depending on the preliminary time of burning (which, *inter alia*, determined the proportion of hot zone present) and the rapidity of stirring to uniformity. In the light of the results for the non-hot-zone-forming oils already discussed, it will be understood that the subsequent course of events depended on the rate of stirring and on the bulk oil temperature. It was found that if the former exceeded (on the scale of our experiments) about 0·07 to 0·08 cu.ft/min and the latter was below about 130° C, flames soon cleared from the surface (as in Fig. 11) leaving an edge fire, which often went out, but could in any case be readily extinguished by cooling the tank walls either internally or externally. Behaviour was thus similar to that of a non-hot-zone-forming oil having a flash-point above 30 to 40° C. If the mixed oil temperature were above about 130° C flames could not be cleared (as in non-hot-zone-forming oil with a low flash-point) and the reduction in the burning rate decreased with increasing temperature. The limiting temperature of 130° C is attained by the rapid mixing of oil of which about 40 per cent has been assimilated into the hot zone. Beyond this condition it is evident that fire cannot be entirely extinguished in Pool fuel oil by stirring alone, although very substantial reductions in the burning rate can be effected.

It was found that, subject to this condition, the initial time of burning did not affect the rate of air flow necessary to clear the surface of flame, except for periods of less than 5 to 10 min. When the experiments were repeated on the large scale (9-ft dia tank; 4 in dia inlet at the centre base) this conclusion was confirmed and the limiting air-flow was found to be about 5 to 6 cu.ft/min with 14 ft depth, rising to about 8 cu.ft/min with 3 ft

depth. About 8 cu.ft/min was also found to be the critical rate with 14 ft depth and air injected into the side of the tank, about 1 ft above the base.

In the course of experiments on both small and large scales a curious effect was repeatedly observed, for which we have found no complete explanation. This consisted of a temporary reduction in the fire intensity during the period in which the hot zone was being cooled by stirring. In those cases where the hot zone was cooling uniformly it appeared that this reduction commenced at about 130° C and ended at 120° C or below. If cooling were slow, the phenomenon was very clearly defined, and in extreme cases took the form of complete clearance of flame apart from the edges. An edge-fire formed in this way could not be extinguished merely by cooling the walls of the tank. The rekindling following this temporary effect was often very rapid. With rapid cooling (either a high stirring rate or a low proportion of hot zone before mixing) the effect was sometimes not visible.

The temporary flame clearance could of course be obtained with air-flow rates inadequate to clear flames from the surface after the oil had been uniformly mixed. At such reduced rates, the manifestation was followed by a period of more or less normal burning, during which the bulk oil temperature was below 120° C and there was presumably a temperature gradient at the surface. In these circumstances the uniform oil temperature rose steadily (*cf.*, non-hot-zone-forming oils) and when it again reached about 120° C there was a second manifestation of temporary flame clearance which ended at about 130° C (after long delay due to retarded heating) with a gradual increase of the fire intensity. It is clear that this upper limit of 130° C corresponds with that above which no rate of air stirring can finally clear the surface of flame, but the significance of the lower limit of temperature is not apparent.

(2) *Crude Oils.* The general behaviour of the crude oils on air-stirring was similar to that of fuel oil, except that, although by an adequate flow of air and provided the mixed-oil temperature was not too high, the rate of burning could be greatly reduced, flame was never entirely cleared from the surface. The phenomenon of temporary flame clearance was also not observed, but no thorough investigation of this point was carried out and it is possible that the appropriate conditions were not reproduced.

In Table XII limiting conditions for maximum reduction in the fire are given approximately. Within these conditions the burning rate was reduced to negligible figures and only an ethereal flame played over the oil surface. All the oils had open flash-points.

TABLE XII.

Conditions for Maximum Control of Crude-oil Fires.

Crude oil.	Limiting air flow (cu.ft/min).	Limiting mixed oil temperature (° C).
British	<0·1	104–127
Iranian	0·04	90–95
S.W. Texas	<0·1	77–99

Although reasonable rates of stirring reduced the flame intensity and rate of burning very considerably, it was found that, while stirring continued, the rate of transmission of heat into the oil itself was actually greater than by the accumulation of the hot zone in normal burning. The increase was generally by a factor of two or three.

Where an inadequate stirring rate was used the same observation was made with fuel oil. The importance in the case of crude oils lies however in the fact that this result cannot be avoided (except possibly by a very fine adjustment of stirring rate) whereas with fuel oil an increase in the air rate will clear away the flames. It is evident that with crudes, stirring is in itself an incomplete solution to the problem of extinction.

(3) *Pool Motor Spirit.* It was not anticipated that stirring would be of practical value in connexion with petrol fires and only two experiments were carried out, both with unleaded spirit. In one, stirring was applied when the hot zone occupied about one third of the total depth, giving a mixed spirit temperature of 52° C, and in the other, somewhat after conversion of the cold spirit had been completed and when the oil was at a temperature of 121° C.

In the first case it was found that there was an optimum rate of stirring for reducing the burning rate. Thus with 0·1 cu.ft/min of air the previous burning rate of 1·17 lb/min was reduced to 0·33 lb/min, but at 0·17 cu.ft/min it increased to 0·85 lb/min and at 0·3 cu.ft/min to 1·3 lb/min. At the same time, the rate of heat absorption by the liquid became 50 to 100 per cent greater than represented by the normal assimilation of spirit into the hot zone.

In the second case a similar range of air-flow rates slightly increased the gross rate of loss by burning, but reduced the rate of heating of the oil from about 0·4° C/min to a very low figure.

It appears then that, as was anticipated, the use of stirring does not offer much practical advantage in the case of motor spirit. During the first stage the moderate reduction in burning rate is outweighed by the accelerated transfer of heat to the liquid which hastens the undesirable condition in which the bulk spirit reaches 100° C. In the conditions prevailing after complete conversion to hot zone, however, stirring is definitely advantageous in that it almost stops heating up of the liquid, and probably obviates superheating, which, as has been shown earlier in this paper, may contribute to an eruption with motor spirit.

Oil-jet Stirring.

Experiments on the large scale (9-ft dia tank) using oil-jet stirring of Pool fuel oil showed qualitative effects to be the same as with air stirring. In a series of tests, the results of which are summarized in Table XIII, a 13 to 13½-ft depth of oil was burned for 10 min in each case. The jets used for the vertical reinjection of oil through the tank base were ½, ¼, and ⅛ in bore, placed either 1 ft off centre or 1 ft from the side. In each test the phenomenon of temporary flame clearance was observed, after which the flames cleared from above the jet, quickly at first but more slowly with increasing radius. In each case (excepting Expt 28) the flames receded to the wall and were ultimately extinguished.

TABLE XIII.

Summarized Results of Jet-Stirring Tests.

No.	Jet bore (in).	Position of jet.	Pump pressure (lb/sq in).	Oil flow rate (gal/min).	Time to complete extinction (min).
30	$\frac{1}{2}$	Centre	60	25	9
25	$\frac{1}{2}$	Side	100	50	$17\frac{1}{2}$
27	$\frac{1}{4}$	Side	200	17	10
28	$\frac{1}{8}$	Side	280	7	Only 50% surface cleared.
29	$\frac{1}{8}$ and $\frac{1}{4}$	Side	175	19	$6\frac{1}{2}$

From the results it can be said that the arrangements in Tests 30, 25, 27, and 29 had very roughly the same effects, but that the arrangement in 28 was not successful. The near-central position was more effective than the side and the actual volume rate of oil circulation required to clear the given area of flame was diminished by decreasing the jet size so as to procure a higher nozzle velocity at the expense of an increased pump pressure. The pressure necessary to render the $\frac{1}{8}$-in jet effective could not be attained by the pump in use.

Direct Injection into the Hot Zone.

Only brief reference will be made to the small-scale experiments on this subject, as the technique does not appear to be of practical value. The effects were examined of pumping cold fuel oil from the bottom of the tank and re-injecting it horizontally into the hot zone either through an inlet in the side of the tank or through a floating radial distributor suspended at a controlled distance below the surface.

It was found that with this arrangement the hot zone could be cooled without apparently disturbing the oil surface sufficiently to procure final extinction. As a consequence, the phenomenon of temporary flame clearance could be clearly observed without the supervention of a final surface clearing effect. Under these conditions the two minima, one with falling and one with rising temperature, could be easily reproduced. It was seen that in both cases clearance of flames from the surface was associated with spreading froth which, as it were, drove the flames before it right to the edges. When the minimum was of long duration, as it was always on the upward temperature path, and on the downward path with low rates of oil circulation, the edge fire was very liable to go out.

As this method did not result in cooling of the oil surface itself, it had no effect at all on non-hot-zone-forming oils. Thus, in a series of experiments with Pool gas oil, no level of horizontal injection of the cold oil could be found at which there was a retarding effect on the burning rate.

Conclusions and Practical Considerations.

Non-hot-zone-forming Oils.

It appears that fires in bulk oils of the non-hot-zone-forming class can be readily controlled by projecting cold oil from the bulk, by some means, to the surface. With initial oil temperatures of 10 to 20° C total extinction

can be achieved if the flash-point of the oil is above 30 to 40° C. Ease of control is not primarily influenced by the time of burning, but a decreasing depth of oil may hamper practical stirring methods. Under the conditions for total extinction (flash-point and stirring rate above the minimum) the flames are driven to the tank walls, but may be rather persistent there. Their persistence depends largely on the heat content of the tank walls, however, and they are readily extinguished if the walls are cooled either internally or externally.

The most effective method of stirring will be that in which the greatest proportion of energy is devoted to imparting vertical motion to the cold oil. It has been shown that a horizontal component is without value.

In connexion with this class of oil, stirring methods do not appear to offer any advantage over top applied foam as a method of fire extinction. As far as appears at present the latter method is safe except perhaps with oils having a very high surface temperature. As this is likely to be associated with high viscosity, however, the usefulness of stirring methods will be impaired in such cases.

A disadvantage of agitation with this class of oils is that it leads to heating up of the oil bulk if it does not achieve extinction, and in these circumstances may make the oil unsafe for the application of foam.

Experiments with air stirring have illustrated the important rôle of agitation should base-injected foam be applied to these oils. It is clear that much of the effectiveness of this technique would depend on stirring effects, which would however be attended by the disadvantage to which attention has been drawn should the application prove unsuccessful in extinguishing the fire.

Hot-zone-forming Oils.

In hot-zone-forming oils the first effect of agitation will be to cool the hot zone by mixing into it such underlying cold oil as may be present. During this period the phenomenon of temporary flame clearance may be observed under suitable conditions. When the cooling of the hot zone is complete (the oil bulk being then at uniform temperature) the position is similar to that at the commencement of stirring of a non-hot-zone-forming oil, except that the bulk oil temperature is more or less elevated. The possibility of extinguishing the fire by continuing agitation so that underlying oil is projected right to the burning surface depends on the bulk oil temperature not being too high—as indeed it does with the non-hot-zone-forming oils.

Fuel oils. Except in fuel oil fires of the shortest duration, some form of oil agitation appears to be an essential pre-treatment if the application of foam is to be carried out in safety. With this limited object in view lower rates of stirring than are needed to clear the surface of flame will suffice, and there is more scope as to method, for, so long as the cold oil is mixed with the hot zone, it can be introduced horizontally if desired. Obviously the effect of such treatment is to rejuvenate the fire, or to convert it to the semblance of a fire in a non-hot-zone-forming oil.

We have demonstrated the pre-cooling of the hot zone by stirring, followed by foam application in experiments on the 9-ft tank. After

30 min burning, air was introduced from the side inlet near the tank base* at a rate of 2·8 cu.ft/min for 15 min (during which the transitory minimum was observed) and air foam was then applied by top pourer at 85 gal/min. In 2½ min the fire was extinguished without any tendency to slopover. It has already been stated that the direct application of foam after a similar burning period led to a severe slopover. The test was then repeated, but the application of foam was by base injection. This cleared the flames quite smoothly, but left an edge fire which had to be extinguished by cooling the tank walls. It was found that foam was reaching the oil surface at a rate of 43 gal/min, but a sample was found to contain 79 per cent of oil. In the light of this result it would appear that the raising of cold oil by the foam was the principal reason for extinction of the fire.

If stirring is employed at a rate insufficient to extinguish the fire, and with the sole object of cooling the hot zone for the safe application of foam, it is necessary to remember that the rate of heating of the oil is likely to be greater than represented by the normal accumulation of the hot zone. In these circumstances, stirring should be commenced at such a time that when it is complete the foam can be applied without delay. Otherwise, a mixed oil temperature of more than 100° C, which would be unsafe for the application of foam, may be attained earlier than would have been the case without stirring.

If the fire has continued sufficiently long to give a mixed oil temperature of 100° C, or above, slow stirring followed by foam application will offer little advantage. With the fuel oil we have studied, this condition would correspond to rather less than 30 per cent of the depth as hot zone. In such circumstances the most rapid possible agitation would be required in order to cool the hot zone and extinguish the fire before the upper temperature limit for extinction by stirring was reached. In our experiments this temperature was about 130° C and corresponded to about 40 per cent depth as hot zone. Within this condition, adequate rates of agitation directed to the vertical movement of oil can procure complete extinction without auxiliary extinguishing equipment, except possibly some means of cooling the tank walls to get rid of the edge fire.

Stirring has the added advantage with hot-zone-forming oils that it destroys all those conditions that contribute to slopover and boilover. In the former case, apart from making foam application safe it prevents spontaneous frothing during the burning of wet oils, at any rate until the mixed oil temperature reaches 100° C. Even then it would certainly smooth the evolution of steam and break down froth bubbles. Severe boilover due to wet bottoms would be obviated and it is probable that even a minor eruption from this cause, on reaching a mixed oil temperature of 100° C, would be counteracted. The instability of dry oils after completion of the first cycle of hot zone formation is likely to be averted by stirring if it is anything to do with superheating or like effects.

Crude Oils. Most of the conclusions that have been drawn with respect to fuel oils may be applied to crude oils. The exception is that stirring methods are unlikely to give complete extinction in any circumstances.

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* About 8 cu.ft/min of air would be required completely to extinguish the fire under these conditions.

As it is therefore necessary to apply foam to the surface of the oil as a final step, the use of stirring is to be regarded as a necessary pre-treatment for the safe application of foam. As it accelerates the rate of heating of the oil it should only be applied so as to be complete when preparations for the application of foam are also complete.

Motor Spirit. The discovery that motor spirit is a hot-zone-forming oil with a hot zone temperature near to 100° C is of some significance. So long as the temperature is in fact below 100° C it is safe to apply foam, and this safe condition will be maintained as long as possible by refraining from agitation, as for instance in the unsuccessful use of base-injected foam. It seems conceivable that some blends might have a hot zone temperature above 100° C, in which case stirring would be necessary prior to foam application.

In prolonged fires or in fires in shallow vessels complete conversion into the hot zone may be achieved. In this condition, stirring is probably beneficial in preventing superheating, which appears likely to cause slopover.

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Discussion.

Mr J. Rogers: The experiments described go a long way towards explaining what happens when the base injection of foam is resorted to, and they also throw a good deal of light on the experiments which Mr Lancashire described in his paper.

It is stated by the authors that, in order to apply foam satisfactorily by base injection it is necessary to remove the hot zone which forms in certain oils; that is really what happened in Mr Lancashire's experiment. He said that he burned fuel oil, an oil which formed a hot zone about 1½ hours before the foam was applied; so that at that rate we should have had a hot zone about 2 ft deep. Then he applied foam by base injection and there was a slop over; he tried again and there was another slop over; and on the third application he was able to put out the fire. The first slop over removed some of the hot zone, the second removed the rest, and the third application of foam was successful because there was no more hot zone left. Does Dr Burgoyne agree?

DR BURGOYNE: Yes, I do agree with Mr Roger's interpretation of Mr Lancashire's experiment.

MR E. P. LANCASHIRE: The first experiment to which I referred was made with clean oil, fresh from storage, and the period of burning was nothing like so long as in the second trial, when we used the same oil after it had been exposed to severe weather conditions and was consequently very wet, a fact which, I think, added to the hazards.

I should like to refer to the experiments described by Dr Burgoyne and Mr Katan on the injection of air into the tank, which air overturned the body of the oil and finally brought about extinction of the fire. That is very interesting experimentally. But I think they used something like 5 cu. ft per minute on a 9 ft diameter surface; to attain the same results on a 100 ft diameter surface one would need to use a big compressor.

I do feel that the authors' work is very much allied to that which we did in the early days, but if one can adopt a method of injection which brings about stirring and at the same time introduce an inert material which will reach the surface, one is not only cooling the oil, but also providing the requisite coverage.

DR BURGOYNE: It is true that from 5 to 6 cu. ft/min of air was required to extinguish completely a fuel oil fire in the 9 ft tank. We do not know the scale factor for this effect and it is not possible at the moment to say what would be the corresponding requirement for larger tanks.

The rate required to stir away the hot zone preparatory to the safe application of foam was, however, much less—not more than half the above figures. Moreover, the rate for this purpose would appear to be proportional to the burning area, and thus for a 100-ft tank a requirement of 300–350 cu. ft/min is indicated. This at about 15–16/sq.in pressure for a 30 ft depth of oil does not seem out of the question.

It should be emphasized that air bubbling is by no means the only stirring method to be considered, nor is it likely to be the most efficient.

THE CHAIRMAN: I do not know to what extent the fog of security silence has been lifted, but I believe Dr Burgoyne knows a lot which he may or may not be permitted to divulge. (To Dr Burgoyne): What about gas without a compressor? (To the meeting): He is not sure of his position about that. But there is an alternative to the use of very large compressors, which apparently we are not yet in a position to discuss publicly.

MR J. H. HUTCHINSON: Reference has been made to "gentle" stirring, and I wonder whether there is any objection to violent stirring. The reason I ask is that we have been experimenting with the use of stirrers in our crude oil tanks for the purpose of mixing the contents to give an even feed to the stills. A stirrer is inserted into a tank at the bottom manhole, and it gives a violent disturbance and completely mixes the oil. It seems to me that, as we have the equipment available, we should use it in the event of fire to ensure the flow of cold oil from the bottom of the tank to the surface, even though this flow would be more than a gentle flow. An additional advantage of course would be that the equipment could be used practically at once and in any case within the first minutes of a fire.

DR BURGOYNE : I used the word " gentle " in relation to stirring rather comparatively, when suggesting the dissipation of the hot zone as a preparation for the application of foam. I do not think there is any difficulty about the application of stirring rates such as Mr Hutchinson has described. In our experiments with the oil jet stirring method the disturbance at the surface was clearly visible, so that it was effective. I do not see any objection to using very much higher rates of mixing by that method, except possibly in regard to the initial effect. If stirring is *started* very violently there seems to be a slight tendency to spill over; but that is overcome within a minute or so, after which I do not think there is any further trouble.

THE CHAIRMAN : I would add a word of warning. If you are stirring and there is water present, the limit to the rate of stirring is the point at which you send up the water so quickly as to cause a slop over.

A SPEAKER : Are these effects due to radiation ?

DR BURGOYNE : I do not think radiation is likely to penetrate beyond a very short distance into the liquid.

THE CHAIRMAN : I would like to add the comment that the transfer of heat from the flames to the oil in the first place must be by radiation.

MAJOR F. W. JACKSON : I would like to put a question from the firemen's point of view. Dr Burgoyne shows in Table II two lists of oils, and the list on the left seemed to contain most of the oils except crude oil and heavy fuel oil. Is it safe to use either top application of foam or bottom injection of foam on the oils listed in that left-hand column, and is it unsafe to use either top application or base injection of foam on the crude oils after they have been burning for some time ?

Where does motor spirit come in ? Is either base injection or top application reasonably safe for dealing with motor spirit ?

DR BURGOYNE : The oils on the left-hand side of the table are those which do not form hot zones. We see no reason why the top application of foam should not be quite safe with those oils.

We have no experience of the base application of foam to those oils. Dr Clark and his co-authors have something to say in their paper, which will be presented later, about base application to petrol.

It seems that the application of foam, either by top or base application, is liable to be hazardous in the case of the crudes and the heavy fuel oils, but not with petrol, because in that case the hot zone temperature is below 100° C.

COMPANY OFFICER F. HOUGHTON : With regard to the theory that the hot layer is formed by volatilization of the lighter fractions, it seems to me that volatilization should have a cooling effect on the hot layer and not a heating effect, or at least the effect of limiting the rise of temperature. I can only attribute the formation of the hot layer to increase of radiation. I could not follow Dr Burgoyne's remarks on that point.

DR BURGOYNE : As the Chairman has said, the transfer of heat from the flames to the oil in the first place must be by radiation. But the effects

of radiation can scarcely be felt directly at any very great depth in the liquid, and the transfer of heat from the surface downwards must be by the movement of the hot oil. You might bear in mind in that connexion that the hot zone is being stirred continuously by the vapours given off at the lower interface, by the cold oil which is all the time being newly affected; the vapours rise through the hot zone and keep it stirred.

MR E. W. REANNEY: We have seen results based on experiments in a small-diameter tank. Are you satisfied that the results obtained from that tank would be correlated with those obtained in a tank of, say, 100 ft diameter? In the latter case there is a greater distance over which the air can carry away the hot gases and, from the point of view of flame condition, with the larger diameter the periphery would be very much larger.

DR BURGOYNE: I am satisfied that the principle holds for any scale; but I have really no means of saying what is the scale effect on the quantities of air required, if you use that method, or the power that will be required to effect the mixing.

THE CHAIRMAN: Dr Burgoyne suggests that I might add to his remarks on this matter. We have observed two distinct effects. One is the straightforward stirring; the other is extinction, which seems to depend rather upon the velocity introduced, which whips the oil past the hot zone fast enough to prevent it producing any more vapour. We know a good deal about that in tanks of a diameter up to 9 ft, but it would be difficult and hazardous to prophesy from 9 to 100 ft with regard to extinction. I think, however, it is fairly safe to prophesy to any scale in respect of the stirring, which aims only at the removal or dispersion of the hot zone.

A SPEAKER: Is there any specific reason for the use of the 9 ft diameter tank, or did it just happen to be available?

DR BURGOYNE: That was the tank available. It was a 20 ft by 9 ft tank, with one end cut off (making it 16 ft by 9 ft diameter).

DR KATAN: One or two earlier speakers have remarked that the results obtained on the 2-ft and 9-ft diameter scales might not be capable of direct extrapolation to tanks of 100 ft diameter. The point is that if anyone can give us a 100-ft diameter tank we shall be very glad to experiment with it!

PROFESSOR SIR ALFRED EGERTON: I have a grandfatherly interest in this work, and I would like to ask Dr Burgoyne to comment on the source of the flame, because at the surface of a small tank the conditions of ignition are very different from those occurring on a larger surface. The diameter effect may be very interesting; it may be easier to put out a fire if the diameter is larger than if it is small. It is very difficult to ignite any vapour of a hydrocarbon which has not a surface sufficient to provide initiation.

DR BURGOYNE: The question raised by Sir Alfred Egerton opens up a subject on which our experiments do not so far shed much light. We have

done little more yet to elucidate the actual mechanism of flame propagation in oil fires than to use our unaided vision. From this it is evident that the structure of the flames is very variable under different weather conditions, but when there was practically no wind we did observe that flaming occurred in a series of " bursts " with a definite though short time interval in between. Whether one burst of flame served as the source of ignition for the next or whether flame was initiated afresh each time by the hot walls of the tank is an interesting question that we cannot answer at the moment, although photographic evidence might provide the reply. We do know, however, that in comparatively small tanks, to cool the walls effectively is to facilitate extinction considerably, and although it would seem that flame propagation could be continuous in an oil fire it may well be also that its stability in an " established " fire is due to repeated flame propagation emanating from the tank walls.

Written comment by the CHAIRMAN : Surely we are concerned more with the *continuance* of combustion already initiated when fire is actually raging, rather than its initiation from cold start ?

MR V. J. WILMOTH : May I ask Dr Burgoyne what effect a number of stirring points would have on extinction ? I assume that in the small tank the experiments were carried out with one single jet, placed centrally, whereas in a large tank you would have to use a larger number of jets and you would thereby obtain a number of circulation systems.

DR BURGOYNE : I think the remarks made by the Chairman a few moments ago have some bearing on this matter. Where you are concerned with disturbing the surface, it seems to me that the distribution of the points of stirring will facilitate it, because they reduce the radius of action necessary. Not so, I think, in the mixing phase. If you merely want to prepare for the application of foam by cooling the hot zone, it appears to me that the number of stirring points will not matter so much ; but if you want to go the whole hog and clear the surface, then I think you must have distributed injection points.

MR HUTCHINSON : Dr Burgoyne thinks the application of foam to crude oil would be hazardous. Presumably he is referring to ordinary application, and not to application of foam after cooling has taken place. Whatever the means of cooling, whether by circulation of cold oil from the bottom or by other means, I presume that after cooling you could apply foam with perfect safety.

DR BURGOYNE : Yes. I suggested, in so far as I suggested anything practical, that the way in which to deal with crudes seems to be to cool the hot zone and then to apply foam. It would be quite safe.

A SPEAKER : It seems that air stirring might be analogous to base injection, though in a slightly different sense. Base injection, I think, creates a condition similar to that created by an air lift pump in water. If that is so, then surely base injection will take cold oil from the cold layer to the hot layer ; and if we continue that further, surely foam could

take up enough air to overcome the objection to the large compressor. It would probably mean, particularly in a large tank, that base injection would have to be applied at quite a number of points.

I think Dr Burgoyne said that air stirring has practically no effect on the extinction of fires in motor spirit. So far as I know, the base injection of foam with petrol is also very precarious. There are plenty of experiments on record, both in this country and in America, showing its successful action on fuel oil and on paraffin, but there is no record of its successful action on motor spirit.

Is it necessary, in view of the development of the art of foam application, to wait long enough for the hot zone to form before applying foam? Is there a reasonable lapse of time before the hot zone forms to allow the foam equipment to be put into action?

DR BURGOYNE: There is no doubt that stirring is very much involved in base injection, and it is a question in our minds whether there is a great deal of point in including water with the air in such a technique except when dealing with the lightest oils. The presence of the water certainly leads to the frothing trouble with crudes and heavy fuel oils, and it may be suggested that, as a first step anyway, the base injection of the air alone is best.

As to the second question, strictly speaking, of course, the hot zone starts to form straight away. The question is really one of the relation between the amount of hot zone (which is proportional to the time during which the burning has proceeded) and the amount of ullage you have to play with if you are going to cause frothing. I am not really competent to judge how quickly one can get to work on these fires; but perhaps I may repeat that, in the experiment illustrated in the first film, the burning had been going on for only half an hour, and there was an ullage of 2 ft 6 in. Quite a considerable slop over resulted in that case.

THE CHAIRMAN: That is a refinery problem, and there are answers. It is not always easy to keep a hundred men handy! There may be no more than two or three persons present in a large installation storing up to half a million tons of oil at times when no pumping is going on, and the situation may be remote. The time is taken in getting the alarm and mustering machinery into action as well as in bringing into operation whatever fire-fighting technique is adopted.

A SPEAKER: It has always been my experience that slop over is related to ullage. Is there any evidence as to the height to which frothing goes in a tank?

DR BURGOYNE: We have not the answer to that question, but we are endeavouring to find it.

THE CHAIRMAN: An American paper suggested that it was eight times the amount of hot oil; frankly, however, I do not believe it.

MR E. P. LANCASHIRE: I would like to recall the point made about the time lag between the outbreak of a fire and the formation of a hot zone, in

relation to the application of foam by base injection. On that basis I would advocate base injection. Foam is very readily and quickly applied by that means, and it can be done by the minimum of personnel. I argue that it will prevent the formation of the hot zone, and in the meantime steps can be taken to marshal the other necessary appliances to give the order of application to which I referred in my paper.

A SPEAKER: I wonder whether the authors have considered the possibility of using steam for stirring. There is plenty of heat available in the event of a fire; water is cheap enough, and it is also readily available. It seems not impossible that we might arrange some kind of steam generator in the upper part of the tank to effect stirring, provided that steam injection could be used for stirring.

DR BURGOYNE: Apart from the element of the condensation of steam in the cold oil, I do not see any objection in principle to that being done. A certain amount of steam would be lost, but I would not like to say how much off hand.

Vote of Thanks.

MAJOR JACKSON: It gives me very great pleasure to move a vote of thanks to the authors. Dr Burgoyne is a scientist who does not devote all his time to fire research, but he does devote a large part of it thereto; he is one of those with whom I have the greatest pleasure in discussing things, because when you get him on the quiet you can obtain some very useful answers from him. My question in this discussion was rather direct, but he did help us a lot. I do not think that firemen generally knew that it was dangerous to apply foam to the top of heavy oil fires. Before I went to the D.S.I.R. I should quite gaily have put foam on top of heavy oil, even if it had been burning for a long time, and I should not have bothered about a slop over. Now I know better.

The experiments at Llandarcy involve a certain amount of risk. I would not like to mess around with a 9-ft oil tank and face these slop overs; but Dr Burgoyne and his gang go down and appear to enjoy themselves thoroughly. We know also about his palm kernel researches; most of the Fire Services know about that work, at any rate at the ports, and he has established himself as one who takes a really active part in the investigation of fires. I am confident that all will join with me in expressing our thanks to him and Mr Katan.

MR PRACY: It is a most unexpected pleasure to be permitted to second this vote of thanks. I had the opportunity of meeting Dr Burgoyne some time ago at the N.F.S. Staff College at Brighton, and I was then impressed by his great enthusiasm both for preventing fires and for extinguishing them.

(The vote of thanks was carried with acclamation.)

DR N. O. CLARK then presented the following paper, and illustrated the experiments by means of lantern slides and a film.

EXPERIMENTS ON THE RATE OF FOAM APPLICATION TO PETROL FIRES.

By N. O. CLARK, Ph.D., M.Sc., D.I.C., A.R.C.S., E. THORNTON, B.Sc., F.R.I.C. (Fellow), and J. A. LEWIS.

INTRODUCTION.

A STUDY has been made, during the past six years at the Chemical Research Laboratory, of the physico-chemical aspects of foam fire-fighting. By correlating accurate large-scale testing with a laboratory examination of the relevant factors some clarification of the important properties of a foam for our purpose has been effected.[1] These are:

(1) The expansion factor or density;
(2) The specific surface of the foam (*i.e.*, the size of the bubbles);
(3) The stability of the foam at atmospheric and elevated temperature (*i.e.*, the capacity for maintaining its specific surface and liquid or gas content);
(4) The ease of spreading over the fuel surface (a function of the critical shearing stress of the foam and its density);
(5) The resistance of the foam to breakdown under the influence of the fuel by contact with the liquid or its vapour.

The solution of the foaming agent may vary:

(6) In the nature of the agent;
(7) In its concentration.

Three other factors affect the efficiency of a foam installation:

(8) The design of the foam generating apparatus;
(9) The conditions of water pressure, etc., under which it is operated;
(10) The manner of application of foam to the fuel.

Close attention has been paid therefore to measurement and control of these factors.

The semi-large scale testing method used in the earlier correlation can be criticized for its use of a thin film of petrol burnt on water. In the work reported here greater depths of fuel have been used in an effort to meet such criticism.

The aims of this preliminary work have been to establish the nature of the relationship between application rate and control of the fire and to explore the effect of expansion factor on this relationship. It was hoped that some useful practical information on desirable application rates would be gained.

This paper, however, only indicates the kind of control of variables necessary in this field for reliable results. A full investigation would cover parameters other than rate of application and expansion.

Experimental Methods.

Foam was produced from a compressed air generator containing about 200 litres (45 gal) of pre-mixed solution, 3 per cent by volume of a hydrolysed keratin compound. The same manufacturer's batch was used throughout.[4] This generator developed at the Building Research Station,[2] Watford, permits a wide variation in rates of delivery and expansion factor with a useful but limited range of specific surface. It operates on the principle of a large pressure vessel containing a solution of foaming agent and supplied with compressed air, solution and air being led to a common delivery pipe baffled by a series of wire gauzes.

Measurement of factors (1), (2), and (3), and of rate of delivery was effected by the continuous methods described elsewhere.[3] Delivery of foam was made by a 10-cm. (4 in) pipe of total capacity about 55 litres (12 galls). Provision was made for diversion of the foam to waste before reaching the metering devices which were placed close to the delivery end. This permitted a steady running of the generator to be attained before delivery of foam through the meters on to the fire. A further adjustable diversion valve, before the one mentioned above, allowed the rate of delivery to be adjusted without interference with the generator valves.

The fire tank was an open tray, 2·8 metres (9 ft) in diameter, 1·2 metres (3 ft 9 in) in depth, filled from a central product line with Pool petrol (1) to a depth of 0·7 metre (2 ft 2 in). The area of the tank was therefore 6 sq m (64 sq ft).

Surface application of foam was made tangentially six inches above the level of the petrol.

Measurements of expansion factor and rate of delivery were made both by the meters and by sample collection where possible. Specific surface was measured by the meter only and maintained throughout these experiments at 170 ± 10 sq. cm. per c.c.

The radiation from the fire was followed by a simple copper block radiometer 1 metre (3 ft) above the plane of the rim of the tray, distant 5 metres (16 ft) from and directed to its centre, while observation was made of the time of control, *i.e.*, major reduction of the fire. The radiometer readings recorded control of the fire by a reduction in radiation rate to below 1 per cent of the rate without foam application.

In all experiments except No. 36 a five-minute initial burn was allowed before application of foam. No. 36 had a 30 minute preliminary fire.

An initial stock of 14,000 litres (3000 gal) of fuel, frequently mixed by returns from the tray, was reduced to 4500 litres (1000 gal) by the end of experiment 28, when a new stock was obtained and the previous residue rejected.

Experiments 12–36 employed a surface application of foam; experiments 37–42 a bottom injection of foam by the product line.

Experiments 12–32 used a 10-cm (4-in) diameter delivery orifice, 33 a 5-cm (2-in) orifice, and 34, 35 a 2·5-cm (1-in) orifice.

Rates of foam delivery and expansion factors are all reduced to atmospheric pressure.

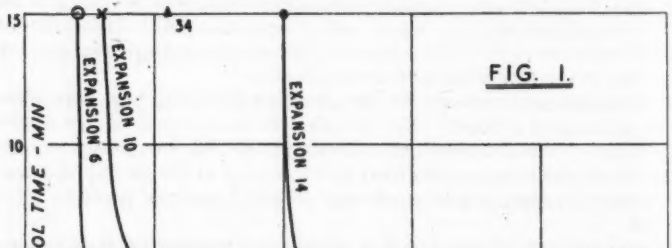
Table I and Fig. 1 record the results of the surface application experiments which fall into four groups; the first three with expansion factors

TABLE I.

Results.

Experiment No.	Time of control, mins.			Delivery rate, gallons per minute.*			Expansion factor ±5%.
	Observed.	Radiometer.	Mean.	Observed.	Meter.	Mean.	
12	1·5	1·5	1·5	48	49	49	10·4
13	2·1	3·2	2·6	38	37	38	11·7
14	∞	∞	∞	—	16	16	10·5
15	1·7	—	1·7	40	40	40	10·2
16	1·8	2·0	1·9	36	33	35	9·9
17	2·3	2·2	2·3	31	28	30	9·8
18	4·8	4·8	4·8	22	16	19	9·6
19	3·1	4·1	3·6	26	21	24	9·8
20	1·5	0·9	1·2	48	60	54	14·1
21	2·1	2·6	2·4	45	49	47	13·5
22	3·5	3·2	3·3	31	36	33	13·5
23	∞	∞	∞	28	33	30	13·9
24	Failed.						
25	2·3	2·2	2·3	39	45	42	13·4
26	1·4	1·6	1·5	32	—	32	6·2
27	1·2	1·1	1·2	44	—	44	6·0
28	5·0	—	5·0	15	—	15	5·9
29	1·5	1·7	1·6	17	—	17	6·3
30	∞	∞	∞	14	—	14	5·8
31	1·9	1·9	1·9	21	—	21	6·0
32	3·8	3·7	3·8	23	—	23	10·2
33	4·5	—	4·5	23	24	24	10·6
34	∞	∞	∞	21	—	21	10·5
35	2·6	2·9	2·7	24	29	26	10·8
36	5·0	3·8	4·4	24	25	25	10·4

* 1 gal/min = 4·5 litres/min.



approximately 10, 14 and 6 respectively; the last with expansion 10 and variations of linear velocity of application, and a variation in initial burning time.

TABLE II.

Experiment.	Time, min.		Radiation rate reduced to, per cent.	Rate of foam delivery, gal/min.*	Expansion factor.
	For changed fire appearance.	For change of radiation rate.			
37	2·1	1·3	31	52	10·7
38	1·1	1·1	52	77	10·6
39	0·9	1·1	67	38	11·3
40	1·1	1·1	50	20	10·8
41	1·8	∞	100	17	10·2
42	1·5	∞	100	108	10·2

* 1 gal/min = 4·5 litres/min.

Table II gives the results of bottom injection experiments. The changed appearance of the fire recorded in the second column was rather an abatement of smoke than an obviously diminished intensity.

DISCUSSION.

Observations were concentrated on the point of control of the fire, that is the point at which a delivery at a very much reduced rate would in time effect extinction, or if suitably directed would effect a rapid extinction. The point is much more definite than that of extinction.

The curves on the figure indicate that each foam on a given fire exhibits a critical rate of delivery below which no progress towards extinction is made. The most desirable expansion factor for the *foam compound solution used* appears to lie in the region of ten.

The curves give some support for Amsel's [5] contention that the resistance of a foam to fire is a function of water content, for instance, division of the application rate by expansion factor for a control time of five minutes gives the values of 2·5, 1·9 and 2·2 for the expansion factors 6, 10 and 14 respectively. In other words, the consumption of extinguishing materials is independent of the expansion factor up to the point of control being obtained over the fire, and it would probably be wiser to specify application rate in terms of water delivery, than to follow the existing practice of foam rate specification, as this would be made less dependent on the efficiency of the apparatus. For the fire used, the critical rate was 16 gal per minute for an expansion factor of 10, *i.e.*, 2·5 gal of water per minute per 100 sq ft of fire. For a fire of long duration (say one hour) it would probably be safe to allow 4 gal per minute of water for every 100 sq ft of area on fires of the order of 100 sq ft.

Experiments 32 to 35 indicate very little dependence on the linear velocity of application.

Experiment 36 indicates an increase in the critical rate arising from

lengthier initial burning. An increase from five to thirty minutes burning gave a displacement of 25 per cent. along the rate axis.

All bottom injection experiments failed to control the fire, not because the foam was destroyed, but presumably because it lifted the petrol.

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Llandarcy.

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Discussion.

Mr E. P. Lancashire: First I should like to say what an excellent paper this is.

The statement is made that the experiments on base injection, as described in the paper, were not effective. I would like to refer to some experiments which we did some years ago on petrol. We used only a small "tank," for the supply position with regard to petrol was not too good, and I could not be trusted with a large volume! For the purpose of our experiments we cut a 9 ft diameter cylinder in half longitudinally, and used one half in a horizontal position; so that we had a vessel 9 ft across at the top, and approximately 4 ft 6 in deep across at the middle. It was divided into two separate compartments by means of a brick bulkhead amidships. We fitted connexions, and filled each compartment with petrol and ignited it. Into the second compartment foam was injected by means of a No. 2 branch pipe, and it put out the fire in that compartment, leaving a very excellent foam blanket on the surface, and at the same time leaving the petrol on the other side of the bulkhead still alight. The area was 130½ sq. ft. We permitted the product to burn for a little more than 1½ minutes and then injected foam, when after 2¼ minutes the fire was out, the consumption of foam compound being about 4 gallons. The experiment has been repeated on several occasions with the same results.

I note that Dr Clark, in his experiments, injected directly at the bottom on the vertical centre line, and it may be this had a bearing on the results that he obtained.

THE CHAIRMAN (Mr E. Thornton): A lot of work has been done, and I am very glad that Mr Lancashire has made his statement concerning at least one of the original successful applications of base injection experimentally. The question is very much in the air, and I suggest that we do not devote too much time this evening to the discussion of what obviously needs far more investigation. The Americans have taken up the matter in a big way, and all the published data indicates that this work is not yet complete; so that at this stage people should maintain open minds and should not take sides for or against this very interesting new development. We cannot discuss it in detail because it is still incomplete. I would just add, however, that in such American work as I have seen reported, no time was allowed for the formation of any considerable "hot zone," the foam being applied within five minutes of the fire starting.

MR H. E. BEDFORD: There is plenty of evidence that base injection is perfectly satisfactory in certain cases, but I do not know of sufficient evidence to warrant its application to gasoline fires. Assurance can be found only by factual tests, not by wishful thinking, and only by such work as we have discussed to-day can a successful technique be evolved.

In the paper by Dr Clark and his co-authors I notice there are references to expansion factors varying between 8 and 12. Later, Dr Clark almost answered the question which has been on my mind for some time, as to what is the necessity for any expansion above 2. In other words, I think Dr Clark said, or implied, that the water content was a prime factor in resisting heat. That being so, it seems to me that if we could have a stable foam with a 2 or 4 or 6 expansion there is no necessity to have anything higher. But it turns on the word "stable." We have heard a lot about "heavy water" in connexion with atomic energy. My suggestion is that foam is "light water." I do not suggest it is anti-atomic; but I do think there is a point there in regarding it as light water—and it is generally admitted that water is the best fire-extinguishing medium because of its inherent properties.

DR CLARK: This question of the base injection of foam into gasoline is important; and I would confine my remarks to gasoline. Obviously, the manner in which we introduce the foam in these experiments is very important. There is no doubt that in our experiments there was a very serious break-up of the surface, and therefore, the foam must have carried petrol with it as it came up.

Our experiments covered expansions from 6 to 14, a rather wider range than Mr Bedford suggested. The evidence is that, if you can hold the water in the foam, then the lower the expansion the better, because the higher the expansion the more volume capacity you have to allow for in inlets; I have no doubt that a foam with an expansion of 2, which did not lose its water so rapidly that its function as a radiation protector failed, would be very valuable. We could use an emulsion which is sufficiently lightened by air to float on the petrol; probably we could make an emulsion between the water, containing foam compound, and the fuel which we are attempting to extinguish, and aerate that to a sufficient extent to make it float. The emulsion would probably give it sufficient viscosity to hold up the air.

I think there is a very wide field for research in the study of dispersed systems of two immiscible liquids and air.

THE CHAIRMAN: You have probably noticed that these experiments stop at the point at which you obtain control; so that it may be true that the water content was all that mattered up to that point. But there is obviously further work to be done to find out what happens when you go further; it may then be untrue, when you try to put on a stable layer, a sort of cork to prevent further ignition.

MAJOR CHANTEAUD: Before parting, I should like to make you aware of the French point of view in regard to the storage of petroleum products in the future. Owing to the constant increase in the capacity of oil tanks, we have to state the maximum storage unit, and the maximum storage unit has been fixed at 26,000 tons. That amount can be put either into one tank or into several tanks. But we find that such a unit would be a constant danger, especially in view of the increase of air traffic. Very often these units will be near airfields; if an aeroplane crashed on such a tank, it is doubtful that the consequent fire could possibly be controlled, whatever appliances we use.

Thus, we have come to the theory that these units must be placed underground. In reply to one of my questions to-day, Mr Lancashire stated that underground storage would be very expensive, and that if a fire occurred in such a tank containing only a small amount of product, it would be difficult to extinguish. We think that, if a fire occurred in a tank of about 150 ft diameter and, say, 60 ft high, it would be still more difficult to extinguish, whatever quantity of liquid the tank contained.

Another factor is that by providing underground tanks we should be preparing for the next war. We all hope there will not be another war; but we never know, and we think it is better to put more money into underground tanks than to risk above-ground tanks.

We also propose to provide underground tanks in industrial areas, wherever the ground is such that that is possible. Where underground tanks cannot be built, we can have semi-underground tanks, which have the advantage over the above-ground tanks that half the capacity is buried below ground level.

With regard to fire extinguishing appliances, we do not think much of the fixed installation. Mr Lancashire has told us that no tank fire has ever been extinguished solely by means of fixed equipment. We rely on mobile equipment, which is certainly much cheaper than fixed equipment, and that can be used everywhere with the least expense. But from our experience of fires during the war we find that, to prevent a fire in one tank setting fire to another, it is best to provide 6-in water mains all over the place, and to provide diffusers from place to place in order to be able to form a water curtain.

We have not yet had experience of what the Americans call atomized water, or fog nozzles, but for over twenty years have used a similar system—the "diffuseur"—which we were the first to advocate. We think, as you do, that the use of mechanical foam is certainly the most efficient way of extinguishing an oil or petrol fire. From the discussions to-day I am

perhaps not very sure in my mind whether it is better to use base injection or top application, maybe because my English is not perfect.

We of the Paris Fire Brigade and the French Institute of Petroleum are very keen to keep in close touch with you gentlemen, because this question is not merely national, but international; the risks exist in every country in the world.

THE CHAIRMAN: We are very gratified, Major Chanteaud, that you should have come all the way from Paris to attend this meeting. I hope that you will convey the thanks of our joint Institutions that you did come here to place your views before us.

Vote of Thanks.

MAJOR CHANTEAUD: It is a great privilege for me to ask the meeting to extend a hearty vote of thanks to the authors of this paper. Last year I came to England and had the opportunity to visit the various laboratories and to meet Dr Clark, and I said then, as I say again this evening, that if some scientists have the bad habit of making rather ordinary things difficult for non-educated people to understand, Dr Clark has the ability to make clear the things which normally are difficult to understand. That is another reason why it is such a pleasure to ask you to accord a hearty vote of thanks to Dr Clark and his co-authors for the paper, and to Dr Clark for the very comprehensive description he has given us of their work.

THE VISCOUNT FALMOUTH: It is a source of very great pleasure to me to second the vote of thanks to Dr Clark and his colleagues for their paper. Dr Clark has been most helpful to the Fire Research Division in regard to this question of foam, and I think we can all agree that we know a great deal more now about foam than we did before he took up the matter at the Chemical Research Laboratory. He has given an indication of the many problems connected with foam and its application which had to be settled before we really began to understand the principles underlying its use. Dr Clark is the author of a monograph on foam which we might almost say is a standard work on the subject. It brings together a lot of information which is quite fresh, and which is due to the efforts of himself and his assistants. On behalf of myself, of the Research Division and of this meeting, I wish to endorse very heartily the thanks expressed to him and his colleagues for their most interesting paper.

MAJOR W. H. CADMAN: It is a great pleasure indeed to me to be allowed to endorse this vote of thanks to Dr Clark and his colleagues. It has been my privilege to see the lay-out of the tanks and the general experimental apparatus used in connexion with their experiments, and I was much impressed by the thoroughness with which the work had been carried out. The site for the work was ideal—they could not possibly have had a better one—and from what I saw I formed a good idea of the tremendous amount of real hard work which has been put into this investigation. Dr Clark and his collaborators are to be congratulated on that work. I appreciate also his frank admission that there is plenty of room for more research in this connexion. It is only by thoroughly investigating the matter still

further, and by painstaking research and accurate measurement, which is the basis of the present paper, that we can really get down to all the fundamentals.

Dr Clark has thrown out an entirely new explanation of the way in which fires are put out, namely, the absorption of the radiation by water. Chemists have generally regarded the extinguishing of a fire as being due to the shutting off of the supply of air or oxygen and so preventing combustion; but that, according to Dr Clark, is only a secondary matter. The primary reason why the foam puts out a fire is the absorption of the radiation by the water in the foam, if I understand his explanation correctly.

I should like to mention a remarkable fire which I saw extinguish itself in Persia. The product consisted of many millions of gallons of petroleum product, stored in an open excavation surrounded by a bund of earth. It was really a large lake of a residue oil remaining from the improvised storage of crude oil before tanks were available at the oilfields.

The lighter and more volatile fractions of this crude had evaporated by reason of the intense summer heat, extending over several years, and the winter rains had accumulated beneath the oil.

This huge volume of oil, several feet deep at the centre and shallow at the edges, caught fire, as the result of some heavy residue oil from a near-by refinery being dumped into the lake. The hot residue oil flowed by gravity from the Stills to the lake but had to pass from the end of a pipe into the air before dropping into this storage reservoir. When the fire was started the temperature of the oil leaving the pipe must have been above its self-ignition temperature.

The quantity of foam and the fire-fighting appliances available were quite inadequate for the local firemen to deal with a petroleum fire of this magnitude.

Then a most remarkable thing happened. After several hours of burning, during which the firemen stood around with spades attending to the bund round the lake and preventing any overflow which might set the native quarters on fire, steam was seen to rise from all round the edge of the lake. This gradually formed a steam canopy, or blanket, over the burning oil, and completely put out the fire.

I do not know whether or not that is an example of steam absorbing radiation, but it is a fact that it extinguished probably one of the biggest oil fires that has ever occurred in any part of the world.

DR CLARK briefly responded to the vote of thanks.

On the motion of Mr Farrell, speaking on behalf of the Institution of Fire Engineers, the hearty thanks of the meeting were expressed to Mr Thornton, to whose good offices was due the invitation extended to that Institution to take part in the discussions.

MR THORNTON briefly responded, and the meeting closed.

DR J. H. BURGOYNE and MR S. S. KATAN (written contribution): We were very interested in Major Cadman's story of the fire that put itself out. We think that the explanation is to be found in the results of our experiments described in the paper on "Fires in Open Tanks". The oil con-

cerned, being a residue, would undoubtedly form a hot zone of high temperature during burning. When this hot zone had assimilated the whole depth of oil it would cause the underlying water to boil vigorously. In a deep tank, such conditions would lead to boil-over, but with a small depth of oil spread over a vast area, such an effect would be precluded. Nevertheless, the vigorous evolution of steam through the oil would cool and stir the latter, ultimately reducing its temperature to about 100° C. Before this, however, as our experiments have shown, the fire would go out.

MEASUREMENT OF OIL DEPTHS.

DETAILED procedures and specifications of apparatus for measuring oil depths in bulk containers were prepared by Panels II and VII of Standardization Sub-Committee No. 1 (Measurement and Sampling) and published (*J. Inst. Petrol.*, 1945, **31**, 40) for comment and criticism.

These procedures together with the apparatus specifications, amended as indicated below, have now been accepted by the Standardization Committee as the Standard Method for Measurement of Oil Depths and recommended for use.

The amendment to the apparatus specifications consists in alteration of the last line of Section 2 (*a*) to read :

> " . . . will be about 6 inches from the inside of the bottom end of the swivel, and exactly 6 inches from the top of the hole in the dip weight."